Temporal Dynamics of Cognitive processing Influence Creativity: Importance of Environmental Setting

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Abstract

Human creativity refers to the cognitive capacity to produce new and valuable information, which often leads to innovations in society and scientific technology. Over a long period of time, many people have been fascinated by the question of how creativity emerges in our brain and how it can be enhanced. Recently, a growing number of studies have revealed that some types of environmental stimuli can enhance human creativity. Further, specific temporal dynamics of cognitive processes are crucial for acquiring creative ideas. However, how the temporal dynamics of creativity are influenced by the environment remains unclear. Through a literature review of neural and psychological research, this study aimed to elucidate the environmental settings that enhance cognitive performance. We found that each stage of the temporal dynamics of creativity may differently be correlated with neural function. Further, environmental factors may have various, and sometimes contrasting, effects on the temporal dynamics of creativity. We propose a hypothesis that the optimal environment condition varies depending on the stages of temporal dynamics since each stage requires different cognitive processes. However, there is a need for future studies to elucidate how creativity is modulated by social conditions and the physical environment, as well as whether there are differences in the ideal environment for individual and group creativities. Nonetheless, this is the first study to clarify the influence of environmental settings on the temporal dynamics of creativity from the perspective of neuroscience and psychology.

Keywords: Creativity, Temporal dynamics, Environment, EEG, Oscillation, Alpha

1. Introduction

Creativity is an aspect of human nature that involves the formation of novel and valuable ideas (Robert, 2011; Kozbelt et al, 2010; Lubart & Mouchiroud, 2003). This phenomenon allows individuals to produce innovative information, which facilitates growth in our society. Given that creativity is crucial for society, there has been extensive interest in the factors that enhance creativity.

It is widely accepted that creativity is strongly dependent on an individual's personality (Barron & Harrington, 1981). For example, compared with individuals with low creativity, those with high creativity are open to new experiences, and are self-confident, ambitious, and intrinsically motivated (Feist, 1998; Prabhu et al., 2008). Therefore, there has been extensive research on personal characteristics to determine the crucial factors for creativity (Abdullah et al., 2016; Baas et al., 2013; Barron & Harrington, 1981; Chávez-Eakle et al., 2012; Eysenck, 1993; Feist, 1999, 2010; Furnham & Bachtiar, 2008). However, personality is often innate, attributable to a person's genetics, and a crucial component of identity (Briley et al., 2014; Lucas et al., 2004). That is, personality is generally stable over time, and does not change easily (Lucas et al., 2004; Briley et al., 2014). Therefore, a growing body of researchers have investigated whether specific environmental factors can enhance human creativity.

Amabile's componential model of creativity (Amabile, 1982; 1996; 2018) found that creativity requires both external components, such as the surrounding environment, and internal components, including creativity-relevant processes, motivation, and domain-relevant skills. These studies showed that high creativity can be acquired when a person is working in a highly "*creative environment*" and goes through the "*creativity-relevant process*". That is, human creativity can be modulated by the interactions between creativity-relevant process and the associated environment.

In this paper, we discuss the creativity-relevant process and how environmental settings influence the creativity-relevant process by reviewing neural and psychological research. We emphasise that specific temporal dynamics of the cognitive process are crucial for creativity and that these dynamics allow for enhanced human creativity. Further, the

optimal environmental condition may vary, and sometimes contrast, depending on the phase of temporal dynamics of creativity since each phase requires different cognitive processes.

2. Temporal Dynamics of Creativity

2.1. Various Cognitive Processes are Crucial for Creativity

Over the past decades, it has become clear that the most important cognitive process for creativity is divergent thinking (Guilford, 1967). Divergent thinking involves the generation of creative ideas by proposing multiple solutions; contrastingly, convergent thinking focuses on a finite number of solutions. Another aspect of the creativity-relevant thought process is abstract versus concrete (specific) thinking. Abstract thinking refers to a cognitive processing style that captures physically absent objects or ideas. Abstract thinking is associated with creativity, whilst concrete thinking is aligned with an analytical approach (Friedman & Förster 2000, 2001, 2005; Huang et al., 2015). Compared to concrete thinking, abstract thinking has been suggested to promote diverse solutions by reducing the dominance of any single solution (Ward et al., 2004).

Although creativity does not generally require convergent thinking, it can be employed together with divergent thinking (Lundsteen, 1986). For example, after exploring multiple possible solutions through divergent thinking, convergent thinking can be applied to organise and structure solutions to identify the most optimal one. Therefore, convergent thinking is crucial for elucidating various solutions and determining creative and valuable ideas. Moreover, employing both divergent and convergent thinking could yield creative and valuable ideas.

Such complementary interaction between these thinking types to yield elaborate creative ideas could be explained by Wallas' Art of Thought model (Wallas, 1926). The model implies that a creative idea emerges through at least four stages involving different cognitive activities:

(i) Preparation: A problem is identified and considered.

- (ii) **Incubation:** *Conscious effort at creativity is not made; however, unconscious or subconscious attempts are applied.*
- (iii) **Illumination:** *The moment when a creative idea bursts into conscious awareness.*
- (iv) **Verification:** *The idea is consciously verified, evaluated, elaborated, and finally applied.*

In the preparation stage, individuals define the problem, gathers information required for the solution, and sets up criteria for verifying the solution's acceptability. Here, individuals may also use various ideation methods to develop a creative idea from multiple perspectives. However, they often provoke habitual, rather than creative and novel, thinking. In the incubation stage, they allow their mind to wander to let it contemplate and work out the problem. In the illumination stage, ideas arise from the mind, which provide the basis of a creative response. Accordingly, this stage describes the classic "eureka!" or "aha" moment of insight, which is popularly considered as a classic characteristic of a creative person. Finally, during the verification stage, they evaluate whether the creative idea yielded in the illumination stage satisfies the criteria defined in the preparation stage. Further, they polish the idea to make sure that it is both useful and novel.

Notably, different cognitive processes are required to reach each of the stages. For example, the illumination stage is the only period when a creative idea actually emerges, which undergoes convergent elaboration in the next stage (i.e., verification). Furthermore, in the preparation stage, people are intentionally and consciously eager to have a creative idea; however, it does not arise immediately. Nevertheless, this stage is necessary for clearly recognising the problem to resolve. The verification stage is an intentional and conscious process; however, unlike the preparation stage, the individual is not seeking a novel idea. Instead, they consciously evaluate and verify the idea yielded in the illumination stage. Compared with the preparation and verification stages, the incubation and illumination stages are more subconscious and incidental processes.

Except for illumination, each stage can last for minutes, weeks, and even years; however, illumination is often very brief and involves a tremendous rush of insights within a few minutes or hours. The verification stage allows an abstract idea emerged at the illumination stage to transform into a concrete form. Therefore, the performance at the

verification stage may be facilitated by convergent or concrete thinking rather than divergent and abstract thinking.

2.2. Neural Correlates of Temporal Dynamics of Creativity

The temporal dynamics of creativity may be correlated with neuro-oscillatory activities. Specifically, neural oscillation revealed by electroencephalography (EEG) is associated with the cognitive states, including awareness and consciousness (Engel & Singer, 2001), and has been used to investigate the neural correlates of creativity. For example, oscillatory powers at the alpha band (8-12 Hz) can be increased during creative ideation (Dietrich & Kanso, 2010), as well as the relaxed mental state with the individual at rest but not tired or asleep. In contrast, alpha powers are generally decreased by executive function at the frontal lobes, which control a set of cognitive processes that are necessary for attentional control or concentration on a specific task (Diamond, 2013). The frontal lobes are mainly involved in executive function (Dalley et al., 2011; Dosenbach et al., 2008; Heekeren et al., 2008), and another study reported that their function partially impedes the neural processing of creativity (Flaherty, 2005). This implies that creativity does not require executive function and that creativity is negatively correlated with neural processing underlying executive function.

In contrast, there is also evidence supporting a role of executive function in the creative process (Krumm et al., 2018). Specifically, studies suggest that creativity can result from an interaction between creative and other cognitive activities, including executive function (Beaty et al., 2018; Sharma & Babu, 2017). A functional magnetic resonance imaging (fMRI) study suggested that this interaction is reflected in different neural networks (Beaty et al., 2018). First, the default mode network (DMN), which comprises the cortical midline and posterior inferior parietal regions, is involved in spontaneous “*idea generation*” (Zabelina & Andrews-Hanna, 2016; Mason et al., 2007) and mind wandering (Buckner et al., 2008). Second, the executive control network (ECN), which comprises the lateral prefrontal and anterior inferior parietal regions, is involved in “*idea evaluation*” (Beaty et al., 2016). Third, the salience network (SN), which comprises the bilateral insula and anterior cingulate cortex, mediates switching between the DMN and ECN, and the conveying of candidate ideas originating from the DMN to the ECN for idea evaluation (Beaty et al., 2016, 2018). It has been suggested that these networks could

interact and complement each other, and that creative persons may have higher global efficiency across these networks (Beaty et al., 2015).

The aforementioned neural networks also correspond to neural oscillatory activities at the alpha band. A previous study on neural oscillation activities in idea generation and evaluation reported increased alpha power at the beginning of idea generation, which was followed by a decrease and a subsequent re-increase (Schwab et al., 2014). Additionally, an fMRI study examining brain activity during poetry composition and assessment (revision) found attenuation of dorsolateral prefrontal cortex (dlPFC) activity during composition, which was amplified during revision (Liu et al., 2015). The dlPFC is particularly involved in ECN and contributes to executive function and idea evaluation. This indicates that idea generation and evaluation are mutually critical in the manifestation of real-life creativity.

Taken together, high creativity can be achieved through interaction between different types of cognitive processes including free and intuitive thinking for idea generation, and attentional and concrete thinking for idea evaluation. The three neural networks (DMN, ECN, and SN) and four creativity stages (preparation, incubation, illumination, and verification) indicate that the creative process is not static. Rather, it is a dynamic process involving explicit and implicit processing for idea generation and evaluation. In particular, it is assumed that the verification stage requires concrete and convergent thinking processes and is possibly correlated with the decreasing of alpha power and neural function of ECN. In contrast, the incubation and illumination stages are largely associated with idea generation and may therefore require relatively divergent and abstract thinking processes. Thus, these two stages may facilitate the contribution from the DMN and represent the increasing of alpha power.

Previous studies have suggested that the environmental condition influences various cognitive activities, including thinking and creativity (Choi et al., 2014). We hypothesise that the ideal environmental conditions vary for each creativity stage (i.e., preparation, incubation, illumination, and verification) due to differences in the cognitive activities required for each stage. However, to our knowledge, there has been no study on the optimal environmental conditions for each stage. In the next section, we discuss how

different environmental conditions could influence creativity with respect to the four creative stages and temporal dynamics of creativity.

3. Environmental Effects on Creativity

Wallas construed that the greatest mathematical discoveries by Henri Poincaré (1854-1912) resulted from specific periods of incubation that did not involve conscious mathematical thinking (Wallas, 1926, p.81). To solve a problem, Poincaré went into the woods because he thought that such an environment could facilitate creative problem solving (Choi et al., 2014). The specific environmental condition during the incubation stage may induce creativity at the subsequent illumination stage. In addition, Wallas' four-stage model of creative processes suggests that the ideal environment should vary depending on the cognitive stage in the temporal dynamics of creativity. Actually, previous studies have assessed the influence of environmental conditions on different cognitive activities (see Table 1). They indicated that some types of environmental factors are optimal for a specific task but not a creativity task, and suitable environmental condition depends on the type of task. However, as suggested in the four-stage model, a creative idea emerges through various and sometimes contrasting cognitive activities including convergent and specific thinking as well as creative thinking. We assume that the different cognitive activities that are important for the four stages are facilitated by different environmental conditions. That is, an optimal environmental condition may vary, depending on the phase of the temporal dynamics of creativity.

Table 1. Environmental factors on cognitive performance and the possible creative stages according to Wallas' model.

Cognitive status	Assumed stages	Factors	Task types	References
Explicit process	Preparation (or verification)	An inverted-U Model between temperature and performance (optimal temperature of 21.6°C)	Objective work performance tests based on 24 previous studies (including text processing, simple calculations, and length of telephone customer service time)	(Seppanen et al. 2006)
		PMV between -0.5 and 0	Office work simulation, neurobehavioral tests, and Stroop	(Lan et al. 2011)
		PMV = -0.21	Thinking and typing tasks	(Kosonen and Tan 2004)
		Thermal Sensation Vote (TSV) = -1.4 (for pupils)	Tests for attention, perception, memory comprehension, and logical reasoning	(Zhang et al. 2019; Jiang et al. 2018)
		TSV between -1 and 0.14 (for adults)	Arithmetical calculation, typing, logical reasoning, and memory tasks	(Zhang et al. 2019; Lan et al. 2011; Jensen et al. 2009; Geng et al. 2017; Cui et al. 2013)
		Short time exposure to mild cold stress with an increased core body temperature	Cognition tasks	(Hancock et al. 2007)
		Higher ventilation rate	Work performance tests based on 24 previous studies (including text	(Seppanen et al. 2005)

		(gets saturated over 45L/s-person)	processing, simple calculations, and length of telephone customer service time)	
		Low CO ₂ and VOCs concentration	Cognitive function assessment using the Strategic Management Simulation Tool	(Allen et al. 2016)
		Red colour	Detail-oriented task (e.g., memory and proofreading tasks)	(Mehta and Zhu 2009)
		Low ceiling	Item-specific processing	(Meyers-Levy and Zhu 2007)
Implicit process	Incubation or illumination	Moderate noise level	Remote Associates Test (RAT), Alternative Uses Tests (AUT)	(Mehta et al. 2012)
		Moderate and high noise level	Abstract processing RAT and AUT	(Mehta et al. 2012)
		Blue colour	RAT and AUT	(Mehta and Zhu 2009)
		Dark colour	Structured imagination task, AUT, creative insight problems	(Steidle and Werth 2013)
		High ceiling	Relational processing	(Meyers-Levy and Zhu 2007)
		Perspectives regarding natural environments or exposure to natural materials, as well as high spatial and visual complexity levels	Subjective creativity potential rating by viewing photograph	(McCoy and Evans 2002)

Simple external tasks not related
with the primary creativity task
that maximise mind wandering

Unusual Uses Task (UUT)

(Smallwood and Schooler 2015),
(Baird et al. 2012)

3.1. Thermal Conditions: Air Temperature and Predicted Mean Vote

To clarify the relationships between the environmental condition and cognitive performance, Choi et al. (2014) described a theoretical model of the environmental effects on cognitive performance, which was a revision of a cognitive load model described by Paas and Van Merriënboer (1994). They suggested that increased cognitive activity could attenuate feasible information processing. Specifically, the environmental stimuli that draw attention could increase cognitive loads and affect cognitive performance. For example, air conditions affect cognitive performance through oxygen-related physiological mechanisms (Lan et al., 2011). Arterial blood oxygen saturation is positively correlated with cognitive performance quality (Scholey et al., 1999). Compared with a thermally neutral environment (around 22°C), a warm environment (around 30°C) lowers arterial oxygen saturation and reduces the will to exert effort, attention, and concentration (Lan et al., 2011). Cognitive tasks, including attention and concentration, could be critical for the preparation and verification stages of creativity. Therefore, this previous study suggested that a warm environment could attenuate cognitive activities involved in the preparation and verification stages.

Previous neural findings are somewhat consistent with these reported effects of air temperature on creativity. A study on the EEG characteristics of thermal comfort (Yao et al. 2009) suggested that the global relative EEG powers of alpha waves were increased under thermally neutral (24-26°C) and slightly cool environments, as well as decreased in environments at > 29°C and < 21°C. Other thermal factors can also affect an individual's perception of the thermal environment. For example, many researchers use the predicted mean vote (PMV), which is an overall thermal comfort index (Fanger, 1970) involving six primary factors: environmental factors of air temperature, relative humidity, air velocity, thermal radiation, and personal factors of metabolic rate and clothing. The PMV ranges from -3 to +3, where negative values indicate conditions are too cold, values close to 0 indicate comfort, and positive values indicate too hot. Kosonen and Tan (2004) suggested that different combinations of these thermal factors can yield similar PMV values. Further, they suggested a correlation of task-related performance with human perception of the thermal environment, which can be represented by the PMV value. A PMV value of -0.21, which ranges from thermal neutral to slightly cool, allows optimal performance for

thinking and typing tasks. As aforementioned, increased alpha power could be a biological marker of the incubation or illumination stages of creative thinking. Creativity mental processes may require a similar optimal thermal temperature that allows comfort and induces alpha activities. Contrastingly, other mental activities, including concentration and attention, may require a slightly colder temperature for optimal performance (Al Horr et al., 2016; Fisk 2000).

3.2. Other Factors: Space Size, Sound, and Colour

A high indoor ceiling has been suggested to activate freedom-related conceptualisation and improve relational processing, while a low ceiling activates confinement-related conceptualisation and improves item-specific processing (Meyers-Levy & Zhu, 2007). Therefore, indoor environmental conditions, including temperature and working space size, could influence cognitive performance during each creativity stage. Previous studies have mostly focused on the different indoor conditions that enhance creativity. Nonetheless, this paper suggests that the optimal indoor environment is dependent on the creativity stage according to Wallas's four-stage model.

Acoustic noise could be another important factor affecting cognitive performance, including creativity. Increased noise-inducing distraction, which improves the construal level and abstract processing, has been suggested to subsequently enhance creativity (Mehta et al., 2012). Notably, relative to low noise levels, moderate and high noise levels induce abstract processing. However, creativity is only enhanced by moderate noise levels given that very high noise levels attenuate information processing. Neural studies have examined the oscillatory activities induced by sound of white noise (a random signal having equal intensity at different frequencies, such as sound of a non-existent radio station), with two studies reporting significantly decreased alpha rhythm (Horii et al., 2004; Kawasaki et al., 2009). These authors suggested that white noise induces unpleasant feeling, which decreases alpha powers. However, they did not compare the oscillatory activities caused by different noise levels. An fMRI study on neural connectivity modulation under different noise levels (Rondinoni et al., 2011; 2013) suggested that low noise levels allowed networks to reach wider areas and allowed for higher oscillatory activity in the motor/auditory cortex, supplementary motor network, and frontal executive network (Rondinoni et al., 2013). Contrastingly, higher noise levels

induced an overload in the DMN, which suggests that they affect DMN-related processes, including mind wandering and creative thinking. These findings suggest that network activities are influenced by acoustic noise levels.

Other studies have demonstrated that colour can influence cognitive performance. For example, red and blue environments allowed better performance of memory/proofreading and creative tasks, respectively (Mehta & Zhu, 2009). These authors proposed that blue (reminiscent of the ocean or sky) activates an approach motivation and enhances creative task performance, while red (reminiscent of stop signs or warnings) activates an avoidance motivation and enhances detail-oriented task performance. A previous study on neural oscillatory activities representing colour stimuli (Yoto et al., 2007) reported differences in modulated alpha activities across various colour stimuli (red, blue, and green). Moreover, there were differences in the subjective scores for heavy, excited, and warm feelings between red and blue conditions. Compared with blue, red was found to induce increased alpha oscillation. On the other hand, there was no significant effects of green stimulus when compared to red and blue. This suggests that compared with blue, red elicits an anxiety state, which results in greater brain activity involved in perception and attention processes. Further, another study on the effect of light and darkness on creative performance (Steidle & Werth, 2013) reported that darkness allowed freedom from constraints, which facilitated global and explorative processing style, and consequently facilitated creativity. Further, this increased creativity disappeared when using a more informal indirect light or when evaluating ideas.

3.3. Our Hypothesis: Importance of Temporal Dynamics

Taken together, the evidence suggests that a blue, dark room with moderate sound noise, a high ceiling, and thermal neutral could enhance creativity, while a red room with a low ceiling and low noise, and slightly cool may enhance detail-specific task performance (Mehta et al., 2012; Mehta & Zhu, 2009; Meyers-Levy & Zhu, 2007; Al Horr et al., 2016; Fisk, 2000). We hypothesise that environmental stimuli that induce moderate cognitive loads or comfort are essential for creativity. For example, moderate sound generally induces a small degree of cognitive load and enhances creativity (Mehta et al., 2012).

Such environmental effects can be reflected in neural activities, including neural oscillations and networks. Creative thinking increases alpha power; moreover, oscillation activity reflecting slight cognitive loads may be a marker of cognitive status for yielding creativity (e.g., incubation period). Based on Wallas' four-stage creativity model, proper environmental settings may allow better performance in each creativity stage (Fig. 1). For example, the verification stage could require task-specific performance involving explicit cognitive efforts since individuals are not seeking novel ideas; rather, they consciously verify and evaluate specific generated ideas. Contrastingly, the incubation and illumination stages require more creative performance involving more implicit and subconscious processes. Based on current literature, we hypothesise that red colour, low noise levels, a low ceiling, and slightly cool induce better performance during the preparation or verification stage, whereas blue colour, moderate noise levels, a high ceiling, and thermal neutral may facilitate the incubation or illumination stage. Future studies should attempt to elucidate the environmental effects on the temporal dynamics of creativity, with respect to oscillatory or network activities.

Fig. 1 Temporal dynamics of thinking that could enhance creativity and possible neuro-oscillatory correlates.

4. Discussion

In this study, we reviewed the effect of environmental stimuli on each cognitive stage in the temporal dynamics of creativity. Previous studies have reported the types of environmental stimuli that enhance or inhibit creativity. However, most studies did not consider environmental effects on temporal dynamics until creativity emergence; rather, they assessed the effects on the period when individuals actually realised a creative idea. This paper discussed that the optimal environmental condition can vary depending on the cognitive stage in the temporal dynamics of creativity. Environmental factors may have various, and sometimes contrasting, effects on the temporal dynamics of creativity. We hypothesise that the optimal environment condition varies for each creativity stage since they involve different cognitive activities.

To reveal creativity emergence, it is important to elucidate the environmental effects on the preparation and incubation stages of creativity. Additionally, the verification stage, which involves idea evaluation rather than generation, is critical for manifesting the idea in reality. Notably, studies have suggested that different cognitive activities, including abstract vs. specific and divergent vs. convergent thinking, are differently influenced by external environmental stimuli (Choi et al., 2014; Dul et al., 2011). This is suggestive of different optimal environmental conditions for different stages in the temporal dynamics of creativity, including verification and preparation. This is the first study to clarify the environmental effects on cognitive performance at each stage. Further, we suggest that environmental stimuli that induce moderate cognitive loads may be essential for enhanced creativity.

4.1. Toward Understanding Environmental Influences on Neural Dynamics

Environmental conditions are widely considered to modulate creative capacities; however, the underlying causal mechanisms remain unclear. Some studies have reported environmental effects on neural oscillation at the alpha band (8-12 Hz) (Horii et al., 2004; Kawasaki et al., 2009; Yao et al., 2009; Yoto et al., 2007) and DMN (Rondinoni et al., 2011; 2013), which is a critical neural function and network for creativity (Dietrich & Kanso, 2010; Fink et al., 2006, 2009; Lustenberger et al., 2015; Schwab et al., 2014). Yoto and

colleagues indicated that different stimuli have different effects on the mental state (e.g., anxiety or calmness), which modulate neural processing (Yoto et al., 2007). For example, they suggested that blue elicits stronger arousal, while red may elicit an anxiety and therefore cause a strong attention than the colour blue. Therefore, environmental stimuli may indirectly modulate creativity by influencing mental state, physiological state, and neural activities. This hypothesis is consistent with previous findings. For example, previous studies have suggested that creative mental activity may require thermally neutral temperature for comfort to induce alpha activities. Contrastingly, other mental tasks, including concentration and attention, may require a slightly colder temperature for optimum productivity (Al Horr et al., 2016; Fisk, 2000).

Taken together, the previous studies suggested that different environmental stimuli have different effects on cognitive processes, which modulate neural processing. Furthermore, they indicated that optimal environmental factors depend on the type of task. However, as suggested in Wallas's four stage model, creativity is not a static but dynamic phenomenon through various cognitive processes involving idea generation and evaluation. There has been no neural study of the environmental effects on temporal dynamics of creativity.

We hypothesise that providing the optimal environmental condition based on the temporal dynamics of creativity processes could improve performance in each stage (Fig. 1). Specifically, based on previous findings, we hypothesise that environmental stimuli that induce attention and concentration (e.g., red colour, low noise levels, and a low ceiling) result in better performance during the preparation or verification stages. Contrastingly, environmental stimuli that induce spontaneous and subconscious processing (e.g., blue colour, moderate noise levels, and a high ceiling) may facilitate performance in the incubation or illumination stages. Moreover, these environmental effects can be reflected in neural activities, including neural oscillations and neural networks. Further research is required to elucidate the environmental effects on cognitive performance in each creativity stage rather than just the exact period that creativity emerges.

4.2. Other Challenges and Future Prospects

Environmental factors of creativity are comprised of physical and social components, including human relationships and office atmosphere (De Alencar & De Bruno-Faria,

1997; Stokols et al., 2002). A previous study reported that the physical environment exerts less influence on social-organisational environment; moreover, they both have lesser influence than individual personality (Dul et al., 2011). Further, creativity is modulated through intricate interactions between environmental factors and personal characteristics (Amabile, 1982, 2018; Amabile et al., 1996; Woodman et al., 1993). This study focused on the effects of the physical environment on individual, rather than collective (or group), creativity. Future research should elucidate the relationships between social and physical environmental effects, between individual and group creativities, and between personality and creativity.

Notably, the current model of creativity does not fully explain all of the components necessary to be accepted as creativity. Creativity is a process of producing something valuable as well as original (Robert 2011; Kozbelt, Beghetto, & Runco 2010; Lubart & Mouchiroud, 2003). Despite evidence supporting the importance of environmental stimuli and temporal dynamics of cognitive processes for the production of new information, little is understood about how and why people can recognise such information as valuable and creative. This fundamental question will be a key to understanding where creativity comes from, and how a creative idea should be approved and utilised for innovation and growth in our society, as well as for temporary satisfaction.

In conclusion, this study investigated environmental conditions that enhance cognitive performance at each stage in the temporal dynamics of creativity. We emphasised that the optimal environmental condition varies depending on the cognitive stages in the temporal dynamics of creativity. However, future studies are warranted to elucidate how the social and physical environment modulates creativity, as well as which environmental conditions are optimal for individual and group creativities. Nevertheless, this is the first study to clarify the environmental effects on the temporal dynamics of creativity from a neuroscience and psychological perspective.

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Competing interests

The authors declare that they have no competing interests

Availability of data and materials

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Authors' contributions

T.D. prepared the figures and wrote the original draft of the manuscript. F.Q., H.T., H.Y., and Y.N. reviewed and edited the manuscript. T.D., F.Q., H.T., H.Y., and Y.N. finalized the manuscript.

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