Cognition 141 (2015) 26–35

Contents lists available at ScienceDirect

Cognition

journal homepage: www.elsevier.com/locate/COGNIT

The working memory Ponzo illusion: Involuntary integration of visuospatial information stored in visual working memory

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ARTICLE INFO

Article history:
Received 5 December 2014
Revised 9 April 2015
Accepted 10 April 2015
Available online 24 April 2015

Keywords:
Visual working memory
Visual perception
Information integration
Ponzo illusion

ABSTRACT

Visual working memory (VWM) has been traditionally viewed as a mental structure subsequent to visual perception that stores the final output of perceptual processing. However, VWM has recently been emphasized as a critical component of online perception, providing storage for the intermediate perceptual representations produced during visual processing. This interactive view holds the core assumption that VWM is not the terminus of perceptual processing; the stored visual information rather continues to undergo perceptual processing if necessary. The current study tests this assumption, demonstrating an example of involuntary integration of the VWM content, by creating the Ponzo illusion in VWM: when the Ponzo illusion figure was divided into its individual components and sequentially encoded into VWM, the temporally separated components were involuntarily integrated, leading to the distorted length perception of the two horizontal lines. This VWM Ponzo illusion was replicated when the figure components were presented in different combinations and presentation order. The magnitude of the illusion was significantly correlated between VWM and perceptual versions of the Ponzo illusion. These results suggest that the information integration underling the VWM Ponzo illusion is constrained by the laws of visual perception and similarly affected by the common individual factors that govern its perception. Thus, our findings provide compelling evidence that VWM functions as a buffer serving perceptual processes at early stages.

1. Introduction

Visual working memory (VWM) is a mental system that briefly stores and manipulates information in a visuospatial form (Baddeley, 1992, 2003, 2012). As the term "working" emphasizes, working memory enables active maintenance and manipulation of multiple pieces of transitory information and contributes to a variety of cognitive tasks through the interaction with other cognitive systems.

Although the specific term distinguishes working memory from the previous concept of short-term memory, they were used synonymously in many studies, which implicitly regarded working memory as a higher-level processing stage subsequent to perception that stored the final outputs of perceptual processes. For example, working memory was usually defined as a limited capacity system that stores information to provide an interface between perception, long-term memory, and action (Baddeley, 2003), implying that the job of working memory is merely to store the perceptual output and forward it to the subsequent processes. According to this *final-output view*, the content in working memory has completed its perceptual processing; therefore, working memory does not need to interact with visual perception. The model of phonological working memory (Vallar & Papagno, 2002; see also Baddeley, 2003 for a review) assumes a feedback path from phonological store to phonological analysis, describing how

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http://dx.doi.org/10.1016/j.cognition.2015.04.010
0010-0277/

they interact with each other to process the input auditory stream; however, no equivalent structure is explicitly suggested for VWM in the theoretical models such as Baddeley's model (Baddeley, 2003, 2012), and there seems to be no feedback route for the content of working memory to participate in perceptual processing. This single-pathway feedforward viewpoint has changed in contemporary cognitive psychology. An increasing number of studies have focused on the intertwining relationship between visual perception and VWM. Studies of attention showed that common attentional resources and mechanisms are involved in both VWM and perception (Anderson, Vogel, & Awh, 2013; Awh & Jonides, 2001; Chen & Cowan, 2009; de Fockert, Rees, Frith, & Lavie, 2001; Kiyonaga & Egner, 2014; Mayer et al., 2007; Woodman, Vogel, & Luck, 2001). Eye movement research revealed the mutual influences between VWM and saccades (Bays & Husain, 2008; Hollingworth, Matsukura, & Luck, 2013; Shao et al., 2010), and indicated that VWM plays a critical role in integrating information collected across separate gaze fixations (Hollingworth, Richard, & Luck, 2008; Irwin & Andrews, 1996). In addition, perception was found to be impacted by VWM maintenance (Kang, Hong, Blake, & Woodman, 2011; Saad & Silvanto, 2013; Yang & Flombaum, 2014). These findings demonstrate that visual perception and VWM interact extensively. Inspired by this line of research, a new perspective of VWM had emerged, suggesting that VWM is not merely a higher-level process subsequent to perception but rather represents an important component of online perception: VWM interacts with different subsystems of visual perception in an online manner, storing different types of intermediate perceptual representations and serving in the assembly process when constructing perceptual representations. Evidence for such an *interactive view* has been provided by Gao, Gao, Li, Sun, and Shen (2011), who conducted a series of experiments to show how VWM and online perception interact during information selection, consolidation, and maintenance. For instance, outputs of parallel perception can be automatically stored as integrated objects while those requiring serial attentive processing cannot. Thus, the laws of visual perception also govern the storage mechanism of VWM.

According to this interactive view, VWM works as a buffer that dynamically supports online perceptual processing; thus, a core assumption of this theory is that VWM is not necessarily the terminus of perceptual processing. The information entered into VWM will be further processed if needed, and this continuing perceptual processing will occur automatically without top-down goals or task setting. This viewpoint is fundamentally different from the final-output view. However, direct evidence for this assumption is still lacking. Previous studies have revealed that VWM interacts with perception in many cognitive tasks but could not provide clear clues whether VWM content undergoes perceptual processing through this interaction. Current theories cannot precisely predict this question either. For example, Gao et al.'s (2011) interactive model describes how VWM interacts with visual perception during object storage but does not specify what will happen after the information has completed its processing as visual objects and been stored into VWM.

To provide a direct test for the interactive view's core assumption, we focused on spatio-temporal integration to examine whether visual information continues to undergo perceptual processing *after* it has entered into VWM. Information integration was chosen because VWM likely plays a crucial role as an online buffer for saving temporally separated visual fragments: when visual inputs are discontinuous in time and space, VWM enables temporary storage for the scattered intermediate representations produced by the perceptual system; once sufficient visual inputs have accumulated, the fragments can be integrated into an intact visual representation. Assuming that VWM and visual perception continue to interact intensively with each other to process the stored information, we hypothesize that visual information inside VWM will be integrated *involuntarily*. It should be noted that spatio-temporal integration occurs between visual percepts and visual images stored in VWM when participants were explicitly required to perform the integration (Brockmole, Wang, & Irwin, 2002; see also Di Lollo, 1980 for an earlier study on iconic memory). However, our focus here is to examine whether such integration is able to occur involuntarily without explicit instruction, even in the case where integration is irrelevant to the task, because VWM should respond naturally to the need of perceptual processing as a buffer according to the interactive view. In addition to involuntary integration, as an even stronger hypothesis, we propose that this integration will be constrained by the laws of visual perception. The current study used an illusory figure to demonstrate the involuntary *VWM integration*[1]: parts of the illusory figure were sequentially presented to participants, creating a situation in which VWM is needed for information integration, to examine whether these figure parts will be integrated to produce the illusory percept. Illusions are a significant characteristic of visual perception in that certain images are perceived with a systematic "error" pattern. The presence of such illusions provides a powerful indicator that VWM integration is performed in the same manner as perceptual integration. Thus, we devised a novel paradigm to directly test the hypothesis that integration occurs in VWM and that it is constrained by perceptual laws.

Specifically, the Ponzo illusion (Ponzo, 1910) was adopted to investigate VWM integration. Fig. 1a shows a simple version of the Ponzo illusion (i.e., actual stimuli used in the current study), which contains a pair of horizontal lines with the same length, drawn on a background consisting of two converging lines. Typically, the upper horizontal line appears longer than the lower one. A common explanation[2] for this illusion is that the converging

[1] *VWM integration* refers to the visual integration of spatio-temporally separate visual information stored in VWM. *Perceptual integration*, on the other hand, refers to the online integration of visual information that is simultaneously available in the visual field.

[2] Note that other explanations for the Ponzo illusion exist, such as the low-pass filter theory (Ginsburg, 1984), the assimilation theory (Pressey & Epp, 1992), and the tilt constancy theory (Prinzmetal, Shimamura, & Mikolinski, 2001). As we were concerned about whether VWM integration works in a perceptual manner, and not the specific reasons for the Ponzo illusion per se, we adopted the widespread "perspective hypothesis" explanation for convenience sake.