Cognition 162 (2017) 124–132

Contents lists available at ScienceDirect

Cognition

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

Original Articles

The perceptual and phenomenal capacity of mental imagery

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ARTICLE INFO

Article history:
Received 20 July 2016
Revised 6 February 2017
Accepted 8 February 2017
Available online 23 February 2017

Keywords:
Visual imagery
Capacity limits
Mental representations
Binocular rivalry

ABSTRACT

Despite the brain's immense processing power, it has finite resources. Where do these resource limits come from? Little research has examined possible low-level sensory contributions to these limitations. Mental imagery is a fundamental part of human cognition that bridges cognition with sensory representations. Hence, imagery serves as a good candidate sensory process for probing how low capacity limitations might extend down the processing hierarchy. Here we introduce a novel technique to measure the sensory capacity of mental imagery, while removing the need for memory and any direct subjective reports. Contrary to our dynamic phenomenological experience, we demonstrate that visual imagery is severely limited by the perceptual and phenomenal bottleneck of visual representation. These capacity limits appear to be independent of generation time, depend on visual feature heterogeneity, are attenuated by concurrent retinal stimulation and are endowed with good metacognition. Additionally, the precision of visual representation declines rapidly with the number of stimuli, which is governed by a simple power law. We anticipate that this assay will be important for mapping the limits of human information processing.

1. Introduction

Despite the great processing power of the human brain, when we are asked to remember or process multiple things at once our performance tends to decline with more items (Cowan, 2001; Franconeri, Alvarez, & Cavanagh, 2013; Halford, Cowan, & Andrews, 2007; Miller, 1956). These capacity limits are found across most cognitive domains, such as general intelligence (Neubauer & Fink, 2009), multi-tasking (Monsell, 2003; Rogers & Monsell, 1995), auditory and visual short-term memory (Bays & Husain, 2008; Grimault et al., 2014; Luck & Vogel, 1997; Vogel & Machizawa, 2004) and visual attention (Fougnie & Marois, 2006; Palmer, 1990). Much of the research into human cognitive capacity limits to date has focused on high-level working memory and attentional capacity limits, however exactly where these capacity limits originate is still an open question. Surprisingly, relatively little research has examined any low-level sensory contributions to these limitations, such as the inherent two-dimensional map-like representation of the visual cortex, which likely intrinsically limits the amount of visual information that can be concurrently held. Mental imagery is a primary part of human cognition that bridges high-level cognition with low-level sensory representations via functional sensory simulations. Hence, imagery serves as a good visual process to utilize for probing how low these capacity limitations might extend down the processing hierarchy.

Mental imagery research suggests that both the vividness and sensory strength of mental imagery plays an important role in almost any cognitive function that involves some form of sensory simulation. For example, evidence suggests visual imagery is utilized during visual working memory maintenance (Albers, Kok, Toni, Dijkerman, & de Lange, 2013; Keogh & Pearson, 2011, 2014), when remembering the past or thinking about the future (Byrne, Becker, & Burgess, 2007; D'Argembeau & Van der Linden, 2006), making moral decisions (Gaesser & Schacter, 2014), language comprehension (Bergen, Lindsay, Matlock, & Narayanan, 2007; Zwaan, Stanfield, & Yaxley, 2002), spatial navigation (Ghaem et al., 1997), affective forecasting and eye witness memory (Dobson & Markham, 1993; Gilbert & Wilson, 2007). Surprisingly imagery vividness and strength is somewhat elevated in many psychiatric and neurological populations (Matthews, Collins, Thakkar, & Park, 2014; Sack, van de Ven, Etschenberg, Schatz, & Linden, 2005; Shine et al., 2015). However, despite the overarching importance of visual imagery in daily life, very little research has investigated the capacity limits to what can be imagined. Here we attempt to examine the capacity limits of creating and maintaining mental images in mind in isolation of overt memory.

Much mental imagery research is dependent on self-reported vividness ratings, sensory strength measures, performance on a mental rotation or manipulation task, or through the indirect impact of imagery on other stimuli. Many early visual imagery

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http://dx.doi.org/10.1016/j.cognition.2017.02.004
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studies also asked participants to imagine real-world objects and make comparative judgments about the images. For example, a classic imagery study by Kosslyn, Ball, and Reiser (1978) found that scanning larger images in mind took longer than smaller items, similar to how scanning larger images presented perceptually takes longer than smaller ones. Numerous studies since then have found that imagining a simple picture results in very similar neural and behavioral processes to perception (Ishai & Sagi, 1995; Kosslyn, 1999, 2005; Kosslyn, Alpert, & Thompson, 1997; Kosslyn, Thompson, & Alpert, 1997; Pearson, Clifford, & Tong, 2008). Some early research also delved into the construction of complex visual images, and found evidence that when participants were instructed to imagine an image of an animal as a whole, or to construct the same image which had been broken into parts or 'units' to be 'glued' back together, they took longer in the 'gluing' condition, suggesting it was possible for people to combine multiple units of an image in the mind's eye (Kosslyn, Reiser, Farah, & Fliegel, 1983).

Another experiment found that participants took longer to imagine identical geometric shapes when they were described as being composed of multiple shapes rather than only a few. A further experiment in this paper found that participants were able to construct a scene of multiple images placed close or far from each other based on a verbal description. They found that when a participant scanned from one image to another in the imagined scene it took longer for far versus close images. These studies show that individuals have the capacity to imagine multiple images or 'units' at once however, they do not provide any information about the quality, or capacity limits, of the units the individuals in these studies imagined.

To objectively assess potential capacity limits of visual imagery, independently of limits to working memory, we devised a novel version of the binocular rivalry paradigm, previously used to measure the sensory strength of a single mental image (Chang, Lewis, & Pearson, 2013; Keogh & Pearson, 2011, 2014; Pearson, 2014; Pearson et al., 2008; Sherwood & Pearson, 2010). This method has previously been used to assess the sensory strength of a single mental image through its effect on subsequent binocular rivalry. In this paradigm individuals are cued to imagine one of two binocular rivalry patterns for a few seconds prior to a brief rivalry presentation. Following the imagery formation, there is a higher probability of the imagined pattern being dominant during this brief rivalry presentation. This effect is known as priming and allows us to obtain an objective measure of sensory imagery strength (measured as the percentage of trials primed by imagery, see Pearson, 2014 for a review of the method). This measure of imagery allows us to avoid a reliance on self-report, reaction times, simple featural judgments and any possible effects of concurrent visual attention (Pearson, 2014; Pearson, Naselaris, Holmes, & Kosslyn, 2015).

In the new technique for measuring visual imagery capacity, instead of only imagining a single pattern, participants are cued to imagine from one to seven colored Gabor patches simultaneously for 6 s. To eliminate an overt reliance on memory for the location and structure of each imagined item we presented participants with multiple imagery 'placeholders'. These placeholder cues were two small dark grey lines that informed participants of the horizontal or vertical orientation, color and location for each to-be-imagined colored Gabor pattern around an invisible circular array (Fig. 1A; color cues shown). The logic behind using such cue placeholders was to negate contributions of memory for the location and orientation of the imagined patterns. Following a period of image generation, participants were presented with a brief (750 ms), small, single binocular rivalry display at only one of the many placeholder locations (chosen at random), to probe the prior image strength at that single location, participants then reported the dominant rivalry pattern (red-horizontal, green-vertical or a mix; see Section 2 for stimulus details).

As in prior work (Chang et al., 2013; Keogh & Pearson, 2011, 2014; Pearson, 2014; Pearson, Rademaker, & Tong, 2011; Pearson et al., 2008; Sherwood & Pearson, 2010), the strength of the mental image was taken as percent primed (i.e. the percent of trials in which the imagined pattern matched the reported pattern in subsequent rivalry), compared to the chance score of 50% (equal number of red and green patterns) collapsed across the multiple placeholder locations. We then grouped the data based on the set size of the imagined array to look for any capacity-like set size effects. If there are limitations to what we can imagine we should expect that when subjects are required to imagine multiple images the priming effect of imagery should decrease, while if imagery is limitless, priming should remain constant across all set sizes.

2. Materials and methods

2.1. Participants

A total of 72 participants participated in these experiments (aged from 18 to 35): experiment 1 (N = 4, 2 female), experiment 2 (N = 4, 2 female), experiment 3 (Analyzed participants: N = 13, 9 female, 2 participants were not used in analysis due to attrition and 2 for very high mock priming), experiment 4 (Analyzed participants: N = 7, 3 female, 4 participants were removed from the analysis due to too many mixed percept reports (more than 33%, N = 3) and attrition (N = 1)), experiment 5 (N = 15, 9 female, 7 participants removed due to too many mixed percepts (33%) or low priming (less than 50% for one item)), and experiment 6 (Analyzed participants: N = 6, 4 female, 8 participants were removed due to attrition (N = 2) and due to too many mixed percepts or low priming (more than 33% or priming for one image less than 55%, N = 6).

The majority of participants were students who completed the experiments in exchange for course credit; five of the participants were experienced psychophysical subjects and one of the authors (RK) participated in all of the experiments (except for the background luminance experiment). To ensure the data are not driven by the inclusion of one of the authors all experiments were also analyzed without RK's data in the Supplementary material. All experiments were approved by the UNSW Human Research Ethics Advisory Panel (Psychology) and written consent was obtained from all participants.

2.2. Statistical analysis

For experiments 1–5 repeated measures ANOVA's were carried out in SPSS. All post hoc analysis were two-tailed and controlled for multiple comparisons using the Bonferroni correction.

For experiment 3 the data was normalized using the following equation:

$$\text{Percent Primed}_{(\text{set size }(n))}/\text{Percent Primed}_{(\text{set size }(1))}$$

To analyze the homogeneity data only set sizes 2, 3 and 4 were used. A participant's data was discarded if for any of homogeneity values (100, 75, 66.67 or 50%) there were less than 3 data points. This resulted in a total of 28 participant's homogeneity data being included in the analysis.

For experiment 6 all data functions were fit in MATLAB using a sum of Gaussians and all data was first anchored to 50% priming at the 37 degrees point.

2.3. Apparatus

All experiments were performed in a blackened room on a 27 in. iMac with a resolution of 2560 × 1440 pixels, with a frame rate of 60 Hz. A chin rest was used to maintain a fixed viewing distance of