Cognition 129 (2013) 123–137

Contents lists available at SciVerse ScienceDirect

Cognition

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

Enhanced dimension-specific visual working memory in grapheme–color synesthesia ☆

Devin Blair Terhune *, Olga Anna Wudarczyk, Priya Kochuparampil, Roi Cohen Kadosh

Department of Experimental Psychology, University of Oxford, UK

ARTICLE INFO

Article history:
Received 10 December 2012
Revised 10 June 2013
Accepted 20 June 2013
Available online 27 July 2013

Keywords:
Color-processing
n-Back
Grapheme-processing
Synesthesia
Visual
Working memory

ABSTRACT

There is emerging evidence that the encoding of visual information and the maintenance of this information in a temporarily accessible state in working memory rely on the same neural mechanisms. A consequence of this overlap is that atypical forms of perception should influence working memory. We examined this by investigating whether having grapheme–color synesthesia, a condition characterized by the involuntary experience of color photisms when reading or representing graphemes, would confer benefits on working memory. Two competing hypotheses propose that superior memory in synesthesia results from information being coded in two information channels (*dual-coding*) or from superior dimension-specific visual processing (*enhanced processing*). We discriminated between these hypotheses in three *n*-back experiments in which controls and synesthetes viewed inducer and non-inducer graphemes and maintained color or grapheme information in working memory. Synesthetes displayed superior color working memory than controls for both grapheme types, whereas the two groups did not differ in grapheme working memory. Further analyses excluded the possibilities of enhanced working memory among synesthetes being due to greater color discrimination, stimulus color familiarity, or bidirectionality. These results reveal enhanced dimension-specific visual working memory in this population and supply further evidence for a close relationship between sensory processing and the maintenance of sensory information in working memory.

1. Introduction

Working memory allows the online maintenance of a limited amount of information in consciousness. There is emerging evidence that the encoding of sensory information and the maintenance of this information in a temporarily accessible state in working memory rely on the same neural mechanisms (Jonides, Lacey, & Nee, 2005; Postle, 2006; Serences, Ester, Vogel, & Awh, 2009). For instance, Serences et al. (2009) found that activation patterns in V1 during the maintenance of color and orientation information closely resembled those observed during the encoding of these features. A consequence of this overlap is that atypical forms of perception should influence working memory in the affected sensory modality. This idea can be explored in *grapheme–color synesthesia*, a form of idiosyncratic binding in which an individual involuntarily and reliably experiences color photisms (images or percepts; *concurrents*) when reading or representing numerals and letters (inducers; Grossenbacher & Lovelace, 2001; Rich & Mattingley, 2002; Ward, 2013).

Currently there is no clear evidence that synesthesia affects working memory. However, multiple case studies (Luria, 1968; Mills, Innis, Westendorf, Owsianiecki, & McDonald, 2006; Smilek, Dixon, Cudahy, & Merikle, 2002) and group studies (Gibson, Radvansky, Johnson, & McNer-

* Corresponding author. Address: Department of Experimental Psychology, University of Oxford, South Parks Road, Oxford OX1 3UD, UK. Tel.: +44 (0) 1865 271481; fax: +44 (0) 1865 310447.

E-mail address: devin.terhune@psy.ox.ac.uk (D.B. Terhune).

0010-0277/$ - see front matter © 2013 The Authors. Published by Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.cognition.2013.06.009

ney, 2012; Gross, Neargarder, Caldwell-Harris, & Cronin-Golomb, 2011; Radvansky, Gibson, & McNerney, 2011; Rothen & Meier, 2010; Yaro & Ward, 2007) have documented superior episodic memory for inducer stimuli in synesthetes than in non-synesthete controls (for a review, see Rothen, Meier, & Ward, 2012). Insofar as working memory and long-term memory reciprocally facilitate each other (e.g., Baddeley, 2012), it is plausible that enhanced working memory among synesthetes may subserve superior episodic memory in this population.

Further evidence that synesthesia may affect working memory comes from studies showing that synesthesia impacts performance on selective attention tasks that include inducers (Dixon, Smilek, Cudahy, & Merikle, 2000; Dixon, Smilek, & Merikle, 2004; Mattingley, Rich, Yelland, & Bradshaw, 2001; Wollen & Ruggiero, 1983). For example, synesthetes are slower to identify the color of incongruently-colored than congruently-colored graphemes. Coupled with the recognition that the ability to selectively adjust attention is an important determinant of working memory capacity (Engle, 2002), synesthetes may experience interference costs on working memory from synesthetically-incongruent inducers, as has been found in word recall (Radvansky et al., 2011). However, a recent study found that synesthetes do not differ from controls in a standard Stroop color-naming task (Rouw, van Driel, Knip, & Ridderinkhof, 2013). Given the relationship between working memory and attentional control (Kane & Engle, 2003), this result suggests that synesthetes will not exhibit superior working memory, although it is possible that a synesthesia-specific working memory advantage is present for inducer or concurrent information. Although no model has specified predictions regarding working memory in synesthesia, such predictions can be derived from two competing hypotheses that have been advanced to explain the benefits of synesthesia to episodic memory.

According to the *dual coding hypothesis* (Paivio, 1969, 1986), superior memory may occur when associated verbal and color information is concurrently encoded because the coding of information in multiple slave systems may strengthen the representation of the information. In non-synesthetes, for instance, working memory capacity is greater when stimuli are presented bimodally (e.g., audio and visual) than unimodally (Mastroberardino, Santangelo, Botta, Marucci, & Olivetti Belardinelli, 2008). Thus, synesthetes may display superior memory because they have two associated channels by which a stimulus can be encoded and maintained. For example, a grapheme and its concurrent photism may be maintained separately in a phonological loop and a visual cache, respectively (e.g., Logie, 2011), allowing either representation to be subsequently used to classify stimuli as the same (targets) or different (foils). This hypothesis readily explains enhanced memory for inducers in synesthetes (Gross et al., 2011; Radvansky et al., 2011; Yaro & Ward, 2007), as well as self-reports that synesthetes explicitly use color photisms as a mnemonic aid (Pearce, 2007; Rich, Bradshaw, & Mattingley, 2005; Rothen & Meier, 2010; Yaro & Ward, 2007).

The dual-coding hypothesis makes clear predictions regarding the impact of congruency on working memory. Specifically, if the information in the two channels is congruent, working memory should be selectively enhanced in synesthetes, whereas if the information is incongruent, working memory maintenance should be weakened because of interference in the second channel. This prediction is consistent with the impact of synesthesia on selective attention, as described above. However, the benefits and hindrances conferred on *memory* by a dual-coding mechanism, as reflected in congruency effects on performance, are not always observed in synesthetes (e.g., Rothen & Meier, 2009; Yaro & Ward, 2007). Similarly, in contrast with the predictions of dual-coding theory, two studies found that synesthetes did not differ from controls (Gross et al., 2011) or a normative sample (Rothen & Meier, 2010) in digit span tasks, alternately interpreted as measures of short-term memory or working memory. However, insofar as both studies used verbal material, neither was able to examine congruency effects in working memory for inducer stimuli. An important corollary of this account is that if superior memory is facilitated by a second, ancillary sequence code, then any memory advantage will be restricted to the domain of the inducer and will not be observed with stimuli that do not elicit synesthetic color photisms. This prediction is at odds with the repeated observation that relative to non-synesthetes, synesthetes exhibit superior recognition memory for color stimuli that do not elicit synesthetic experiences (Rothen & Meier, 2010; Yaro & Ward, 2007).

The latter results suggest an alternative account, namely that enhanced modality- or dimension-specific processing among synesthetes facilitates superior memory in the *respective* modality or dimension. This *enhanced processing* hypothesis is supported by results showing that grapheme–color synesthetes exhibit superior low-level visual processing (Barnett et al., 2008), color discrimination (Banissy, Walsh, & Ward, 2009; Yaro & Ward, 2007), precision of color and luminance matching (Arnold, Wegener, Brown, & Mattingley, 2012), and color recognition memory (Yaro & Ward, 2007). Superior low-level visual processing may strengthen representations held in working memory by amplifying incoming sensory information or excluding external noise (Lu & Dosher, 2009) and thereby enhance maintenance of the information.[1] For example, it has been shown that individual differences in color constancy, which enables stable color perception across different levels of illumination, is associated with individual differences in working memory (Allen, Beilock, & Shevell, 2011). Shared mechanisms underlying perception and memory (Chun & Johnson, 2011) similarly entail that enhanced color perception among synesthetes (Arnold et al., 2012; Banissy et al., 2009; Yaro & Ward, 2007) will translate to enhanced color working memory. Crucially, this account predicts enhanced working memory for color in synesthetes irrespective of whether the color functions as a concurrent. However, this hypothesis does not make explicit predictions regarding

[1] Superior low-level visual processing in synesthetes (Barnett et al., 2008) may also entail superior working memory for graphemes and thus would provide an alternative explanation for superior grapheme working memory to the dual-coding hypothesis, although unlike the latter, such an account would not predict Congruency effects.