Vision Research 74 (2012) 102–109

Contents lists available at SciVerse ScienceDirect

Vision Research

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

The effects of cross-sensory attentional demand on subitizing and on mapping number onto space

Giovanni Anobile [a,1], Marco Turi [a,b,1], Guido Marco Cicchini [c], David C. Burr [a,c,d,*]

[a] Department of Psychology, Università Degli Studi di Firenze, Firenze, Italy
[b] Department of Physiological Sciences, Università Degli Studi di Pisa, Via S. Zeno 31, Pisa, Italy
[c] CNR Neuroscience Institute, Pisa, Italy
[d] School of Psychology, University of Western Australia, Perth, Australia

ARTICLE INFO

Article history:
Received 21 December 2011
Received in revised form 8 June 2012
Available online 19 June 2012

Keywords:
Attention
Numerosity
Cross-sensory
Audition

ABSTRACT

Various aspects of numerosity judgments, especially *subitizing* and the mapping of number onto space, depend strongly on attentional resources. Here we use a dual-task paradigm to investigate the effects of cross-sensory attentional demands on visual subitizing and spatial mapping. The results show that subitizing is strongly dependent on attentional resources, far more so than is estimation of higher numerosities. But unlike many other sensory tasks, visual subitizing is equally affected by concurrent attentionally demanding auditory and tactile tasks as it is by visual tasks, suggesting that subitizing may be amodal. Mapping number onto space was also strongly affected by attention, but only when the dual-task was in the visual modality. The non-linearities in numberline mapping under attentional load are well explained by a Bayesian model of central tendency.

1. Introduction

Most adult humans can count. However, we also share an approximate non-verbal system with infants and other animals: a direct visual sense of number (Burr & Ross, 2008). When verbal counting is prevented, we can still see and estimate the numerosity of large sets of items, although with a margin of error (Whalen, Gallistel, & Gelman, 1999), which increases with increasing set size. Small sets of items (up to 4 or 5) are perceived quickly and errorlessly by a system that is at least partially separate from estimation termed "subitizing" (from the Latin *subitus* meaning immediately). A good deal of evidence shows that both subitizing and estimation depend on attention (Railo et al., 2008; Raymond, Shapiro, & Arnell, 1992; Vetter, Butterworth, & Bahrami, 2008). However, it is not clear whether the attentional effects are modality specific, or whether they transfer across modalities. This question is particularly relevant to recent work showing that subitizing is not strictly visual, but also seems to operate in audition (Camos & Tillmann, 2008; Repp, 2007) and touch (Plaisier, Bergmann Tiest, & Kappers, 2009; Riggs et al., 2006).

1.1. Cross-modal attentional effects

Concurrent perceptual tasks of the same sensory modality interfere with each other to degrade performance (Pashler, 1992, 1994). However, evidence for cross-modal interference is conflicting. Bonnel and Hafter (1998) found evidence for audio–visual cross-modal interference for detecting the sign of a magnitude change (luminance in vision and intensity in audition). Spence, Ranson, and Driver (2000) found that selecting an auditory stream of words presented concurrently with a second (distractor) stream is more difficult if a video of moving lips mimicking the distracting sounds it is also displayed. These psychophysical findings are not only consistent with some of the cognitive literature of the 1970s and 1980s (Taylor, Lindsay, & Forbes, 1967; Tulving & Lindsay, 1967), but also with recent neurophysiological and imaging results. For example, Joassin et al. (2004) examined the electrophysiological correlates of auditory interference on vision in an identification task of non-ambiguous complex stimuli, such as faces and voices, and showed that cross-modal interactions occur at various different stages, involving brain areas such as the fusiform gyrus, associative auditory areas (BA 22), and the superior frontal gyri. Hein et al. (2007) showed with a functional magnetic resonance (fMRI) study, that even without competing motor responses, a simple auditory decision interferes with visual processing at neural levels including prefrontal cortex, middle temporal cortex, and other visual regions. Taken together these results imply that limitations on resources for vision and audition operate at a central level of processing, rather than in the auditory and visual peripheral senses.

However, much evidence also suggests independence of attentional resources for vision and audition. For example, Larsen et al. (2003) compared subject accuracy for identifying two concurrent stimuli (such as a visual and spoken letter) relative to

* Corresponding author at: CNR Neuroscience Institute, Pisa, Pisa, Italy.
E-mail address: dave@in.cnr.it (D.C. Burr).
[1] These authors contributed equally to this work.

0042-6989/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.visres.2012.06.005

performance in a single-task. They found that the proportion of correct responses was almost the same for all experimental conditions, either single-task or divided-attention. Similarly, Bonnel and Hafter (1998) used an audio–visual dual-task paradigm to show that when identification of the direction of a stimulus change is capacity-limited, simple detection of visual and auditory patterns is governed by "capacity-free" processes, as in the detection task there was no performance drop compared with single-task controls. Alais, Morrone, and Burr (2006) measured discrimination thresholds for visual contrast and auditory pitch, and showed that visual thresholds were unaffected by concurrent pitch discrimination of chords and *vice versa,* while when two tasks were performed within the same modality, thresholds increased by a factor of around two for visual discrimination and four for auditory discrimination. Also for sustained attentional tasks (such as 4 s of the *Moving-Objects-Tracking* task of Pylyshyn and Storm (1988) separate attentional resources seem to be allocated to vision and audition (Arrighi, Lunardi, & Burr, 2011). Many of these results are in line with imaging studies suggesting that attention can act at early levels, including primary cortices A1 and V1 (Jancke, Mirzazade, & Shah, 1999; Posner & Gilbert, 1999; Somers et al., 1999).

1.2. The effect of attention on numerosity perception

It is well established that even when verbal counting is prevented, humans can estimate the numerosity of large sets of items, albeit with error (usually about 25%). Smaller sets of numbers, up to about four, are enumerated quickly, effortlessly and accurately, termed *subitizing* (Kaufman & Lord, 1949). There has been a long-standing debate as to whether perception in the subitizing range invokes different processes than for larger *estimation* ranges, with evidence for and against (Atkinson, Campbell, & Francis, 1976; Balakrishnan & Ashby, 1992; Mandler & Shebo, 1982; Piazza et al., 2002; Sathian et al., 1999). One reason to suggest that different mechanisms may be involved is that the subitizing and estimation ranges seem to depend on attentional resources in a different fashion. Although subitizing is often thought to be pre-attentive, or at least makes use of pre-attentive information (Trick & Pylyshyn, 1994), several recent studies suggest that subitizing is in fact vulnerable to manipulations of attentive load (Olivers & Watson, 2008; Railo et al., 2008; Raymond, Shapiro, & Arnell, 1992; Vetter, Butterworth, & Bahrami, 2008). Our own studies also go in this direction, showing that for both dual-task and attentional-blink paradigms, precision in the subitizing range is far more affected than in the higher estimation range (Burr, Turi, & Anobile, 2010). We suggested that subitizing and estimation are not identical processes and that a relatively attention-free estimation mechanism could operate over both high and low number ranges, but small numbers, within the subitizing range, can call on an additional attentive mechanism that operates when attentional resources permit over a range of up to four items. In line with this idea, the ERP component P2p, a signature of numerosity processing, emerges in the subitizing range under dual-task conditions (Hyde & Wood, 2011).

Further evidence for this comes from the fact that, like many sensory attributes, numerosity is susceptible to adaptation: prolonged exposure to a more numerous visual stimulus makes the current stimulus appear less numerous, and *vice versa* (Burr & Ross, 2008). With normal free viewing, this effect is limited to numerosity estimation outside the subitizing range. However, under high attention load, numerosities with the subitizing range are also adapted (Burr, Anobile, & Turi, 2011). This suggests that when the supplementary attentive-mechanism for small numbers is impaired (by the dual task), only the estimation mechanism remains, which adapts as it does for high numerosities.

Interestingly, a body of research suggests that the capacity to rapidly enumerate low numbers of items many not be restricted to vision, but could reflect a general perceptual mechanism shared between different senses; subitizing has been shown to operate in audition (Camos & Tillmann, 2008; Repp, 2007), and also with haptic stimuli (Plaisier, Bergmann Tiest, & Kappers, 2009; Riggs et al., 2006). fMRI data also point to amodal representation of numbers. When subjects are asked to estimate numerosities of visual or auditory stimuli, both result in increased activity of a right lateralized fronto-parietal cortical network, independently of the modality of the stimuli (Piazza et al., 2006). Cross-modal interactions in subitizing have also been revealed in a study by Cordes et al. (2001), who showed that precision in tactile number production is affected by a concurrent verbal task.

1.3. Mapping numbers onto space

An interesting aspect of numerosity perception is our ready capacity to map numbers into space, pointing to intrinsic interconnections between number and space (Burr et al., 2010; Butterworth, 1999; Dehaene, 1997). Experimentally, this is studied with the so-called "numberline", where subjects are asked to position appropriately on the line numeric digits, or clouds of dots. Educated adults have no difficulty in doing this accurately, whereas the mapping of young children, children with dyscalculia and unschooled adults show distinct compressive, logarithmic-like non-linearities (Ashkenazi & Henik, 2010; Booth & Siegler, 2006; Dehaene et al., 2008; Geary et al., 2007, 2008; Siegler & Booth, 2004; Siegler & Opfer, 2003). Recently, we showed that limiting attentional resources by a dual-task also results in logarithmic-like numberline mapping (Anobile, Cicchini, & Burr, 2012).

However, the fact that the function follows a logarithmic form does not necessarily imply an intrinsic logarithmic representation of numerosity (Gallistel & Gelman, 1992; Karolis, Iuculano, & Butterworth, 2011). Several alternate explanations have also been put forward, including proportional judgments relative to the ends and centres of the numberline (Barth & Paladino, 2011), related to the well known *central tendency of judgment* (Hollingworth, 1910). We (Anobile et al.) have also explained the non-linearities in numberline-mapping caused by attention deprivation as a Bayesian model of central tendency, similar to that introduced by Jazayeri and Shadlen (2010) to model interval reproduction judgments. The results were well fit by a simple Bayesian model of central tendency, where *central tendency* is a *prior* of variable width, that effectively pulls the higher numbers towards the centre of the numberline (while the lower number remain anchored). We use this model again in this study (see Section 2 for details).

1.4. Goals of this study

The current study was designed to examine the role of cross-modal attentional competition in visual numerosity estimation, using dual-tasks with visual, auditory and haptic distractors on several number paradigms. We had three specific aims: (1) to test the effects of cross-modal attention on numerosity perception for both small (subitizing) and large item sets; (2) study the effects of cross-modal attention on mapping of numbers onto space; and (3) model the mapping effects within a Bayesian framework. We confirm our previous results, showing that high numbers are less affected by attentional demands, while the subitizing range is far more vulnerable. In the low subitizing range, the auditory and haptic distractors were as effective as visual distractors in decreasing precision. The results reinforce other studies in suggesting that subitizing may be an amodal capacity, not restricted to vision. We also replicate our previous results showing that dual-task attention to a concurrent visual task affects numberline mapping (well-modelled by a