What crowds in crowding?

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Introduction

In crowding, the perception of a target deteriorates in the presence of neighboring elements. Crowding is not a new research area but has fascinated researchers for centuries, dating back to 1738, as outlined in Strasburger and Wade (2015). The classic example of crowding is reading where the letters of a word mutually crowd each other. Thus, not surprisingly, crowding research has started off as reading research. In the meantime, crowding has become a primary tool to investigate vision. One main reason is that objects, as letters, are rarely met in isolation in normal life. Thus, crowding is the predominant situation for object recognition for humans and animals, and indeed, the characteristics of crowding are similar in humans and monkeys (Crowder & Olson, 2015).

The interest in crowding and, accordingly, the number of publications on crowding have immensely grown, as evidenced by more than 25 publications in this issue and more than 100 in the past 10 years. The field has not only grown but also undergone significant paradigm shifts. For example, for half a century, a hallmark of crowding was Bouma's law (Bouma, 1970; Pelli & Tillman, 2008). Bouma's law proposes that flankers interfere with a target only when they are presented within a distance of about $e/2$ from the target (e denoting the eccentricity of target presentation). However, recent results have shown that elements presented outside Bouma's window can increase (Chanceaux, Mathôt, & Grainger, 2014; Rosen, Chakravarthi, & Pelli, 2014; Vickery, Shim, Chakravarthi, Jiang, & Luedeman, 2009) or even decrease crowding strength (Manassi, Hermens, Francis, & Herzog, 2015; Sayim, Greenwood, & Cavanagh, 2014; for review, see Herzog, Sayim, Chicherov, & Manassi, 2015). Accordingly, modifications of Bouma's law were proposed (Rosen et al., 2014) or Bouma's law was even questioned (Herzog et al., 2015).

Bouma's law is about the spatial aspects of crowding, and crowding research has been mainly a branch of spatial vision research. Just recent studies have revealed complex and intriguing temporal characteristics of crowding (Yeshurun, Rashal, & Tkacz-Domb, 2015). For example, elements presented before a crowded target can decrease, rather than increase, crowding strength (Manassi et al., 2015; Sayim et al., 2014). Crowding can also be reduced by sharp onset transients of the target (Greenwood, Sayim, & Cavanagh, 2014), and, moreover, the spatial extent of crowding depends on stimulus duration (Tripathy, Cavanagh, & Bedell, 2014). In addition, reaction times correlate well with crowding strength (Hermens & Bell, 2014). It seems that crowding and masking share common spatial and temporal characteristics, at least under certain conditions (Lev & Polat, 2015). Taken together, these results strongly suggest that crowding is a spatiotemporal phenomenon. Next to temporal aspects, crowding has been linked to many other fields, beyond spatial vision,

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such as visual acuity (Yehezkel, Sterkin, Lev, & Polat, 2015), eye movements (Yildirim, Meyer, & Cornelissen, 2015), and object tracking (Holcombe, Chen, & Howe, 2014).

It has been known for decades that target-flanker similarity influences crowding strongly. If, for example, the target and flankers have a different color, crowding is much weaker than if colors are identical (Kooi, Toet, Tripathy, & Levi, 1994). Target-flanker similarity is still a hot topic. For example, when the target is of higher contrast compared with the flankers, crowding is weak. When the flankers have higher contrast, crowding is strong (Rashal & Yeshurun, 2014); Astle, McGovern, and McGraw (2014) found that target-flanker disparity modulates crowding. For example, crowding is stronger when the target appears in front of the flankers compared with when it appears behind them (Astle et al., 2014). Interestingly, categorical aspects influence crowding, showing that crowding is not limited to low-level interactions. Reuther and Chakravarthi (2014) found better performance in conditions in which the target and the flankers belonged to a different rather than the same category. However, Chanceaux et al. (2014) found that complexity predicted flanker interference better than familiarity and better than target-flanker similarity. In the same line, complex flankers interfered more strongly with target identification than less complex flankers (Wang, He, & Legge, 2014).

Not only are the main characteristics of crowding are heavily debated but also its underlying computational mechanisms as witnessed in this issue featuring all major approaches. For example, pooling models prevailed the discussion for decades, where crowding is an inevitable consequence of integrating information from lower-level neurons by higher-level neurons, simply because receptive field size increases along the hierarchy. However, such pooling models are now strongly questioned by holistic approaches, which propose that the overall spatial configuration and perceptual grouping determine crowding (Hermens & Bell, 2014; Herzog et al., 2015; Manassi et al., 2015; Rosen & Pelli, 2015; see also Husk & Yu, 2014). For example, Sayim et al. (2014) showed that an item far outside Bouma's region improved target discrimination when it matched the target compared with when it did not match the target, suggesting that long-range, shape-specific grouping mechanisms counteract "local" crowding. However, other studies criticized the grouping approach, showing that contrast dissimilarity (Rashal & Yeshurun, 2014) and temporal dissimilarity (Greenwood et al., 2014) do not always lead to a decrease of crowding.

On the applied side, crowding is now frequently used as a tool in development (Huurneman & Boonstra, 2015; Doron, Spierer, & Polat, 2015), dyslexia (Gori & Facoetti, 2015), and aging research (Yehezkel et al., 2015). In this line of research, Fortenbaugh, Silver, and Robertson (2015) showed that the individual visual field size explains much of the variability of the lower-upper visual field asymmetry of crowding. This observation provides a potential link between crowding and the cortical representation of the visual field. Crowding is and was reading research. For example, Husk and Yu (2014) showed that zooming in and out single letters in words can reduce crowding and thus ease reading. Yu, Legge, Wagoner, and Chung (2014) found that crowding is the main cause of the reduced visual span and consequently reduced reading speed for vertical text. Wang et al. (2014) found that the complexity of Chinese letters is crucial for reading and that crowding is the dominant factor limiting the size of the visual span. Chanceaux et al. (2014) showed that leftward flankers in the left visual field lead to strongest crowding, reflecting how reading influences visual processing in general.

This special issue makes it clear that crowding is an eminently important topic in many fields of vision research, simply because, as mentioned, elements are seen rarely in isolation. The more than 25 contributions in this issue reflect the many perspectives on the topic. However, they show also that the field is far from a coherent framework, not to talk about a unifying theory. More than ever, crowding is, as Levi (2008) put it, "an enigma wrapped in a paradox and shrouded in a conundrum." More research and more special issues will likely come before the paradox can be resolved.

Keywords: crowding, masking, object recognition, reading

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