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# Object completion effects in attention and memory


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## Summary

Organizing the retinal image into meaningful and coherent objects is one of the fundamental operations of human vision in order to identify relevant perceptual units and objects that are present in the cluttered visual environment. For instance, structures in our ambient array are provided by mechanisms of object completion, which illustrates that the human visual system can connect disjointed image fragments into coherent representations of objects, surfaces, and contours. The current dissertation presents four studies that investigated how object completion determines the allocation of attention and the storage of objects in memory, using psychophysical methods and electroencephalographic (EEG) recording in humans.

The first study (Chapter 2.1) investigated how completion of illusory contours and surfaces in Kanizsa figures modulates the sensitivity of localizing a target probe by using variations of Kanizsa figures. A systematic manipulation of the presented grouping attributes showed clear effects upon visuospatial target detection, with grouping of surface and contour information both determining performance independently, thus supporting a multi-stage model of object integration.

The second study (Chapter 2.2) was performed with the aim to investigate how object integration affects the allocation of attention in time. To this end, Kanizsa-type targets were presented in an attentional blink (AB) paradigm, which revealed effects of grouping that influenced both the initial attentional selection and the subsequent short-term memory consolidation. Grouping therefore clearly facilitates the detection of targets in time with such benefits emerging at early perceptual stages, modulating processing of objects during the initial selection and subsequent consolidation phases.

Using a change detection paradigm with memory displays that contained either ‘composite’ objects, i.e., notched shapes abutting an occluding square, or equivalent non-occluded, ‘simple’ objects, the third study (Chapter 2.3) examined whether the structure of to-be-remembered objects influences what is encoded and maintained in visual working memory (VWM). Composite objects were found to be preferentially stored as globally completed wholes when primed by concurrent simple global objects, but evidence for completion in VWM measures was found to occur only with sufficient available mnemonic resources. This indicates that the representation of a completed object is influenced by contextual information and by

the limited mnemonic resources.

Based on the third behavioral study, the fourth study (Chapter 2.4) tracked the maintenance phase of VWM by means of an EEG component, which is referred to as the contralateral delay activity (CDA), and investigated the relationship between VWM storage and processes of object completion. This study further supports that mechanisms of object completion modulate VWM, with the memory load being determined by the structured representations of the memorized stimuli.

Together, these findings indicate that object completion derives from preattentive processes but these structured representations exert clear influences until later, post-perceptual stages, relating to attentional and working memory processes, as is illustrated by the observed performance modulations in the various cognitive tasks presented in this dissertation. In light of these findings, the current thesis suggests to take relational structures between items and grouping into consideration in relation to both lower and higher levels of cognitive processing.

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# 1 General Introduction

The first part of the introduction presents a review of the most important theories and findings concerning object completion, and their relationships to attention and working memory. The second part explains the motivation for the four studies that constitute this cumulative thesis.

## 1.1 Object completion, attention and memory

Although our perception of objects appears instantaneous and automatic, complex processing is required by which the disjoint visual parts are structured and integrated into larger coherent units, or wholes, so as to identify relevant objects in the real world. The integration of parts into wholes by means of perceptual organization process has been suggested to rely on two forms of visual completion, i.e., modal completion and amodal completion (Michotte, Thines, & Crabbe, 1964/1991). Modal completion refers to perceptual "filling-in" of object borders that are accompanied by concurrent brightness enhancement (see Figure 1a; a Kanisza square; Kanizsa, 1955). In contrast, the perception of occluded areas of objects was termed by Michotte et al. (1964/1991) "amodal completion", using "amodal" to refer to the absence of sensory aspects, e.g., brightness or color, in the parts of objects perceived to be continuing behind other objects (see Figure 1b; an amodally completed square; Kanizsa, 1979). These have been distinguished on the basis of the phenomenological states that they induce, helping to explain how the visual system interpolates missing structure. Despite these differences in subjective experience, both modal and amodal completions involve the connection of disjoint image fragments into a coherent representation of objects, surfaces, and contours.

Grouping operations supporting the object completion are based essentially on closure, collinearity, proximity, and good continuation (Gillam, 1987; see also Wertheimer, 1923/1938; Koffka, 1935), as described in the following. These principles are subordinate to the principle of Prägnanz, which postulates that we tend to order our experience in a manner that is regular, orderly, and simple (Koffka, 1935; Wertheimer, 1922/1938).

*Closure:* Elements that form a closed figure tend to be grouped together.

*Collinearity:* Elements lying on the same straight line are grouped together.

*Proximity:* Objects that are close to each other are perceived as forming a group.

*Good continuation*: A line is most of the time perceived as continuing in a straight way or according to its prior curvature, even though it is actually separated or disjointed by other elements in the visual environment.


**Figure 1.** (a) A Kanisza square (modal completion). This configuration is typically perceived as a white square superimposed on four black circles. (b) An amodally completed square (amodal completion). This configuration is typically perceived as a white square viewed through four apertures of an occluding surface, in which no illusory contours are perceived.

### 1.1.1 Modal completion

The segregation of visual input into coherent objects requires the identification of borders between various image components and surfaces. Normally, the borders of an object are defined by physical differences in luminance, texture, and/or chrominance. However, to perceive objects in the environment as unified wholes, the visual system must often extrapolate from incomplete contour or boundary information. Under certain conditions, contours can also be perceived in the absence of a real, luminance gradient. Modal completion occurs when portions of an object are camouflaged by an underlying surface—because this underlying surface happens to project the same luminance and color as the nearer object, and extrapolated contours are perceived in areas of homogeneous retinal stimulation (see Figure 1a; Michotte et al., 1964/1991).

#### 1.1.1.1 Illusory figures

When contours are not present in the physical stimulus, they are also referred to as “illusory” or “subjective.” Illusory figures seem to have been first displayed and discussed by Friedrich Schumann in 1900. He wrote a series of monographs on the topic of form perception, which became a major focus of Gestalt psychology. The most well-known example of illusory figures was introduced by Kanizsa (1955; Figure 1a), which appears to most observers as a light shape superimposed on black circles. This ‘global’ figure has three associated perceptual features: a brightness enhancement for the illusory surface alongside with the concurrent depth stratification between the illusory surface and the adjacent objects, and a central figure with sharp boundaries. Kanizsa (1955) interpreted the emergence of illusory figures as a consequence of the ‘poor form’ of the inducers. Each inducer on its own is considered incomplete, while the integration of separate elements into a global representation results in a more regular, simple and stable percept. The perceived strength of the illusory figure is strongly tied to the proportion between the diameter of the inducing disks and the side-length of the illusory form. This important factor is called support-ratio (Kojo, Liinasuo, & Rovamo, 1993; Liinasuo, Rovamo, & Kojo, 1997). The perception of the illusory figure is facilitated when the support-ratio is increased, i.e. a small illusory form with comparably big inducers.

#### 1.1.1.2 Contour interpolation and surface filling-in in illusory figures

Computational models offer several possible solutions of how the completion of an illusory figure might be achieved. The interpolation of the missing parts of the bounding contours and the filling-in of the surface of the enclosed area are commonly assumed as complementary mechanisms underlying the modal completion phenomena (Grossberg & Mingolla, 1985; Pessoa, Thompson, & Noë, 1998; Kogo, Strecha, Van Gool, & Wagemans, 2010).

Some suggest a computation that is based on a serial feedforward procedure (e.g., Von der Heydt, Heitger, & Peterhans, 1993), with higher levels of complete object representation reached only after termination of lower level stages. In this view, every processing step is dependent on the termination of the previous step. For instance, local edge information is first extracted and followed by the computation of illusory contours. After the computation of the bounding contours, surface filling-in is then achieved in a last step.

Others propose that perceptual boundaries and surfaces are computed by independent and segregated subsystems (Dresp & Bonnet, 1991; Grossberg & Mingolla, 1985; Grossberg, 2000; Roelfsma, Lamme, Spekreijse, & Bosch, 2002). In general support of these computational principles, Conci, Müller and Elliott (2007a) investigated at which level object attributes in Kanizsa figures influence visual search. They found that global surface information but not the global contour acts as a major determinant of search, suggesting that both attributes of an object can in principle be processed separately from each other. Using a similar method, Conci et al. (2009) investigated the relative contributions of distinct object attributes to the spared access in Kanizsa figure completion in extinction, a disease that commonly occurs after unilateral, parietal brain damage. Extinction manifests in a failure to identify contralesional stimuli when presented simultaneously with other, ipsilesional stimuli. Their results demonstrated that surface information can substantially reduce extinction, whereas contour completions showed comparably smaller influences, further suggesting that the processes of contour interpolation and surface filling-in are to some extent dissociable.

#### 1.1.1.3 Neural mechanisms underlying modal completion

A large number of neurophysiological studies of illusory figure perception complement and help to illustrate computational models underlying the mechanisms of object completion. These findings suggest different views on whether modal completion computation reflects an early or a late process.

A majority of animal studies speak in favour of an involvement of early visual areas (especially V2) in representing illusory contour (e.g., Von der Heydt, Peterhans, & Baurngartner, 1984; Lee & Nguyen, 2001; Grosof, Shapley, & Hawken, 1993; Sheth, Sharma, Rao, & Sur, 1996; Lamme, Van Dijk, & Spekreijse, 1993; Purpura, Victor, & Katz, 1994). Many human imaging studies also found that striate or extrastriate visual areas in human cerebral cortex are activated during the perceptual grouping operations involved in illusory figure perception (Hirsch et al. 1995; Ffytche & Zeki, 1996; Murray et al., 2002; Ritzl et al., 2003). Since only early visual areas contain neurons with small receptive fields for encoding information with high spatial precision and feature resolution, these areas are ideal for representing the perceived sharp contours explicitly (Zhaoping, 2003). These findings are consistent with the "bottom-up" view of the contour-detecting mechanisms that are suggested to relate to hardwired neural mechanisms that are excited involuntarily by any visual pattern. The perception of the illusory figure is achieved via lateral, horizontal connections within the primary visual cortex, which connect cells with similar orientation tuning characteristics across the visual field, resulting in local integration of contour elements (Bauer & Dicke, 1997; Bauer & Heinze, 2002; Grossberg & Williamson, 2001; Kapadia, Ito, Gilbert, & Westheimer, 1995; Stettler, Das, Bennett, & Gilbert,, 2002).

More recent fMRI and EEG evidence, however, supports the view that processing of an illusory figure is specifically related to the lateral occipital complex (LOC; Mendola, Dale, Fischl, Liu, & Tootell, 1999; Stanley & Rubin, 2003; Halgren, Mendola, Chong & Dale, 2003; Pegna, Khateb, Murray, Landis & Michel, 2002; Kruggel, Herrmann, Wiggins, & Von Cramon, 2001; Shpaner, Molholm, Forde, & Foxe, 2013; Shpaner, Murray, & Foxe, 2009) and sometimes to the fusiform gyrus (Larsson et al., 1999; Hirsch et al.,1995; Bakar, Liu, Conci, Elliott, & Ioannides, 2008). It has been suggested that the function of the LOC is to enable long-range grouping, which might be particularly relevant to accomplish surface perception (e.g., Van Oostende et al., 1997; Malach et al., 1995). Stanley and Rubin (2003) demonstrated that the filling-in of surfaces in LOC could be attributed to processes of salient region computations in the visual field, while exact contour interpolations may only result from a subsequent feedback process to earlier visual areas. Recent evidence suggests that initial illusory contour sensitivity takes place in the LOC, pooling information in higher order cortical areas as the initial step in contour integration (Shpaner et al., 2009, 2013). These findings indicate a mechanism that involves integration across different levels of the visual hierarchy, with recurrent feedback/feedforward interactions between different regions in the visual hierarchy (Roelfsma et al., 2002).

According to these findings and suggested models, different completion attributes might be represented in separate regions in the ventral visual processing stream and thus make distinct functional contributions to the perception of illusory figures (Seghier & Vuilleumier, 2006, for a review).

### 1.1.2 Amodal completion

One of the most common obstacles the visual system must overcome in order to recognize objects is occlusion, because of the multiplicity of objects and the loss of one spatial dimension during image projection onto the retina. Phenomenologically, we seem to complete occluded objects immediately and effortlessly, despite the fact that parts of objects have no corresponding local stimulus correlate. For instance, in Figure 2, occlusion of the building by the branches of the tree is pervasive in this picture. It is difficult to count the separate surface regions in the optic array bounded by projections of the tree's branches, whereas the perception of the complete building appears to be available automatically and accurately. The visual system has presumably developed efficient strategies to deal with the grouping of partly occluded contours. Their continuity is derived by visual mechanisms of contour completion, in which the visual system fills in missing information, a process known as amodal completion (Michotte et al., 1964/1991). Kellman and Shipley (1991) have proposed a relatability criterion in terms of the positions and orientations of the edges of the contours, to determine whether or not the two contour fragments are part of a single continuous contour. First, if extended linearly, these extensions must intersect and, second, the turning angle of the two edges should not exceed 90° (Ringach & Shapley, 1996; Yin, Kellman, & Shipley, 2000).

**Figure 2.** An example picture of a partially occluded scene.

#### 1.1.2.1 Visual completions in amodal completion

Our visual system rapidly completes a figure that is partially hidden behind its occluder even though we are usually not aware that this involves selecting one out of, in principle, infinite numbers of possible completions for any partly occluded object. It has been suggested that the generation of completions is constrained such that only "compatible extensions" of the visible structure are produced (Van Lier, Van der Helm & Leeuwenberg, 1995). That is, a compatible extension repeats parts of the visible structure thereby leading to a restricted number of interpretations. Examples of how different spatial structures can lead to different visual completions are illustrated by reports on the relative importance of local versus global processes in completion. In addition, an occluded figure together with its occluder could be seen as a mosaic without any occlusion or completion, where mosaic refers to a 2-D cut-out outline shape identical to the visible part of the figure (Sekuler & Palmer, 1992). Examples of these interpretations are provided in Figure 3. By understanding how observers resolve the structural ambiguity of partly occluded objects, we can determine the relative importance of various perceptual organization factors for object perception.

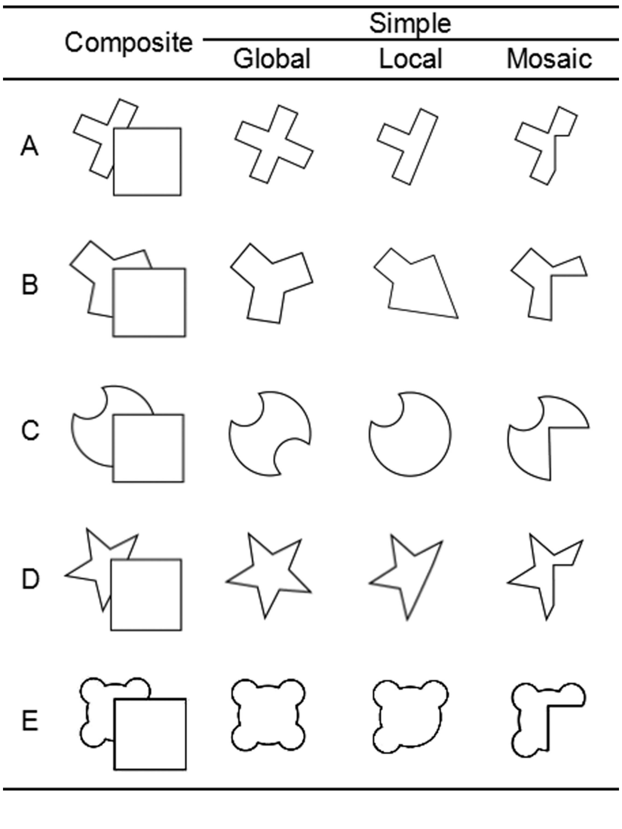


**Figure 3.** Illustration of different forms of amodal completion.

According to a local completion account, completion is based only on attributes of contours and surfaces at or near points of occlusion and the completion itself is as simple as possible. Theories that emphasize local simplicity bear heavily on the role of the gestalt principle of good continuation in pattern completion (e.g., Kanizsa & Gerbino, 1982; Kellman & Shipley, 1991; Kellman & Shipley, 1992; Fantoni & Gerbino, 2003; Fulvio, Singh, & Maloney, 2008). As shown in Figure 3, a local completion is constituted by a linear continuation of the visible contours of the background shape behind the occluding shape. In contrast to local theories, global theories take into account attributes of surfaces and contours of the entire to-be-completed object, with the resulting completed shape being as simple as possible (Buffart, Leeuwenbert, & Restle, 1981; de Wit & Van Lier, 2002). For example, the global completion interpretations in Figure 3 emphasize global properties of the occluded figures, such as symmetry.

In some situations, the local and global completion solutions are identical (e.g., a circle completed behind a square). However, ambiguities are likely to occur in more realistic stimuli, and local and global processes may lead to qualitatively different completions (e.g., Davi, Pinna, & Sambin, 1992). By using ambiguous stimuli, it has been shown that both global and local processes play important roles in completion (Van Lier & Wagemans, 1999; Van Lier, Leeuwenberg, & Van der Helm, 1995). The global solution is favored when the global completion is much more regular than the local completion as indicated by the results that occluded objects lead to stronger priming for globally regular objects than for locally completed objects (Sekuler, Palmer, & Flynn, 1994; Sekuler, 1994; see also Van Lier, 1999, 2001). However, the global processes do not necessarily dominate completion when a very complex completion is required (Sekuler, 1994). Thus, the internal representation of the occluded object lies between the local and global solutions, but it is biased toward the global solution while depending on the spatial structure of the object.

#### 1.1.2.2 Amodal completion goes through distinct stages

Amodal completion results from early visual processing, which is mainly driven by basic stimulus features (Rensink & Enns, 1998). This has been supported by behavioral priming studies showing that amodal completion proceeds rapidly within 200 ms. The amount of occlusion affects the time allowed for completion, with more time needed for highly occluded objects (Guttman, Sekuler, & Kellman, 2003; Rauschenberger & Yantis, 2001a; Shore & Enns, 1997). When researchers explore the time course of visual amodal completion, distinct stages of completion have been identified (e.g., Sekuler & Palmer, 1992; Murray, Sekuler, & Bennett, 2001). Specifically, it is commonly found that a “mosaic stage” may precede completion (Sekuler & Palmer, 1992; Rensink & Enns, 1998; Rauschenberger & Yantis, 2001a).

In a primed matching paradigm, observers view a priming stimulus and then judge whether a subsequently presented pair of test stimuli have the same or different shapes. Sekuler and Palmer (1992) showed that partly occluded objects primed observers’ “same” and “different” responses like complete objects with a prime duration of 100-200 ms; but with short prime durations of 50 ms, the results showed a pattern of priming for occluded objects that was similar to that of mosaic objects. Consistent evidence have been reported using different paradigms (Murray et al., 2001; Rensink & Enns, 1998; He & Nakayama, 1992; Rauschenberger & Yantis, 2001a). In the neural level, the MEG studies showed shorter latencies for a primed stimulus that contains only the mosaic information of a composite stimulus in contrast to a primed completed shape (Plomp, Liu, van Leeuwen, & Ioannides, 2006; Liu, Plomp, van Leeuwen, & Ioannides, 2006; see also de Wit, Bauer, Oostenveld, Fries, & Van Lier, 2006). The evolution of completion process in time has been demonstrated to start from a feature-based (mosaic) to a completed representation in early visual cortical regions (Rauschenberger, Liu, Slotnick, & Yantis, 2006). All these results support that the visual system takes time to arrive at a final visual representation for partly occluded objects from a mosaic representation, and then the visual system treats occluded objects as if they were complete.

#### 1.1.2.3 Contextual effects in amodal completion

Despite the fact that the spatial structure of an object can influence the form of completion, past experience with a particular object or contextual information may also influence whether and how that object is completed. It has been suggested that the relative weights of local and global processes depend on the context (Sekuler & Murray, 2001). Behavioral studies have shown that responses to occluded figures can effectively be primed by their previously viewed unoccluded counterparts (Joseph & Nakayama, 1999; Zemel, Behrmann, Mozer, & Bavelier, 2002). Amodal completion of abstract geometrical shapes can also be influenced by a simple learning task when multiple completions (i.e. global or local completions) of party occluded shapes are perceptually plausible (Hazenberg, Jongsma, Koning, & Van Lier, 2014; see also Lee & Vecera, 2005). And such contextual influences may occur relatively late in processing a given object (Hazenberg & Van Lier, 2016; Hazenberg et al., 2014).

In contrast when considering that completion reveals distinct stages, the contextual views suggest that alternative interpretations of an object may be generated in parallel (Bruno, Bertamini, & Domini, 1997) and different interpretations may dominate due to context within which the object is presented (Peterson & Hochberg, 1983). To support this, distractors in a search display have been shown to bias the interpretation of target composite figure (Rauschenberger, Peterson, Mosca, & Bruno, 2004); Single figures presented first also provided a facilitatory context for local and global occlusion as well as for mosaic interpretations of subsequently presented composite figures (Plomp & Van Leeuwen, 2006). These results directly demonstrate a crucial role of the spatial or temporal context on the completion process and are in accordance with parallel processing of mosaic and occlusion interpretations rather than an explanation that supports separate and sequential stages of processing.

#### 1.1.2.4 Neural mechanisms underlying amodal completion

Activity related to amodal completion was recorded already in early visual areas such as V1 and V2 (Rauschenberger et al., 2006; Sugita, 1999; Murray, Foxe, Javitt, & Foxe, 2004). However, there is also evidence that the perceived completed shapes were processed in higher visual regions such as the LOC (Kourtzi & Kanwisher, 2001), and the activity related to physical features of occlusion patterns was recorded in lower visual areas (Weigelt, Singer, & Muckli, 2007). A serial feed-forward model was proposed for the cortical processes underlying amodal completion: First, local contour information is extracted and processed in primary visual cortex. Second, real contours are assigned to different objects in area V2 and missing contours are filled-in on the basis of basic Gestalt-rules. Finally, the fully completed object is represented in the LOC (Weigelt et al., 2007). This is consistent with the investigations which support that the representation of the completed shape is preceded by a mosaic representation stage (Sekuler & Palmer, 1992; Rauschenberger & Yantis, 2001a; Liu, et al., 2006; Plomp et al., 2006). However, more complex models involving feedback connections might be also possible. Alternatively, amodal completion could result from feedback connections between higher regions and lower tiers in visual cortex (Murray et al., 2004) or be interfered by higher cognitive functions (i.e. visual short term memory; Lee & Vecera, 2005).

### 1.1.3 Grouping and visual attention

Is attention necessary to accomplish the organization of local features into a coherent global percept? There has been considerable work on the relation between grouping and visual attention. Most behavioral evidence comes from visual search experiments in which observers are asked either to search for a group of elements (texture segregation) or to search for an odd element or a predefined target, e.g. a slanted line, in a field of unslanted lines (pop-out experiments; e.g., Triesman, 1982). Processes of spatial attentional selection in visual search start to operate at an early, pre-attentive stage of processing, before stimulus identification is complete (see Luck, 1998a). If, in a target search design, the reaction time (RT) is independent of the number of non-target elements in the display, it is assumed that the underlying processes operate in parallel and are therefore preattentive. Instead, inefficient search would indicate focused attention leading to a serial scanning of candidate target locations. Preattentive processes are identified as those, which occur early, are automatic, fast, and underlie the perception of features which “pop-out”. By contrast, a serial search exhibits a prolongation of response times as a function of the number of distractor items, suggesting the involvement of attentional top-down processes.

Most visual search studies suggest that attention is not needed to achieve visual binding in Kanizsa figure object completion. This is for instance supported by findings which showed pop-out search for a Kanizsa target in a visual search, with search RTs being independent from the number of non-targets (constituting the same inducer elements but which do not form an illusory figure; Gurnsey, Humphrey & Kapitan, 1992; Davis & Driver, 1994; see also Conci, Müller, & Elliott, 2007a, b, 2009). Grouping has been shown to capture spatial attention. Rauschenberger and Yantis (2001b) presented observers with a search task that required detection of a semi-disk target in an array of randomly oriented pacmen. Participants were significantly slower to respond to the presence of such a “local” target when a subset of the segmented disks induced a subjective square. Senkowski et al. (2005) presented an illusory triangle to cue attention to a target region. Efficient cueing of the Kanizsa triangle was revealed (see also Marini & Marzi, 2016).

In the example of amodal completion, search for a notched target disk abutting an occluding square among complete disks and squares turned out to be relatively inefficient, as the notched target is represented as a complete object similar to the distractor disks. In contrast, search was efficient when the notched target was spatially separated from the neighboring square making it more distinct from the surrounding distractor disks (Rensink & Enns, 1998; Rauschenberger & Yantis, 2001a). This suggests that visual search for a partly occluded target is guided by a complete-object representation, with amodal completion occurring pre-attentively (see also He & Nakayama, 1992; Davis & Driver, 1998).

However, in the visual search paradigm, object-based attention is directed to the search target and it is not known whether an illusory figure would be completed when attention is not allocated to the target location. Thus, the question whether grouping requires attention is difficult to answer with visual search findings. Yet, a few studies reported the opposite, namely serial search in variants of an illusory figure search task (Grabowecky & Treisman, 1989; Gurnsey, Poirier, & Gascon, 1996).

In addition to findings from visual search, clinical data from patients with hemispatial neglect and extinction also provide evidence that attention is not required for object completion. These patients show a disadvantage for selection from the contralesional field due to disrupted processes of selective attention (Baylis, Driver, & Rafal, 1993; Humphreys, Romani, Olson, Riddoch, & Duncan, 1994). Despite of their inattention to one side of space, these patients show largely preserved access to integrated object information (Driver, 1995, for a review). They can successfully bisect a line composed from an illusory figure (Vuilleumier & Landis, 1998; Vuilleumier, Valenza, & Landis, 2001) and Kanizsa figures also substantially reduce extinction behavior in a visual detection task (Mattingley, Davis, & Driver, 1997; Conci et al., 2009).

In summary, most studies support the view that factors responsible for grouping exert their influence rather early in perceptual processing, prior to the stage where attention is allocated to a selected item (Triesman 1982; Pomerantz, 1981; Rensink & Enns, 1995; Moore & Egeth, 1997). Grouped objects such as illusory figures could provide salient information, capturing spatial attention and drawing attentional resources (Senkowski et al., 2005; Marini & Marzi, 2016; Rauschenberger

& Yantis, 2001b).

On the other hand, studies also show that the perception of a globally completed object is influenced by top-down attention, either being enhanced by spatial attention  (Martínez, Teder-Salejarvi, & Hillyard, 2007, Moore, Yantis, & Vaughan, 1998), or it might be impeded by a secondary task charging attentional resources (Pritchard & Warm, 1983; Lee & Vecera, 2005). When patients with extinction were presented with multiple items in a visual search task, attentional competition between objects particularly limited integration processes in the contralesional hemifield (Gögler, Finke, Keller, Müller, & Conci, 2016). Therefore, more evidence is still needed to elucidate the relationship between grouping and visual attention.

A novel approach is to investigate how attentional selection is influenced by perceptual grouping over time, given that most previous work focus on the allocation of selective attention across space. The human visual system is limited in its ability to extract durable mental representations from the rapidly changing, continuous flow of information across time. This is reflected in the attentional blink (AB) phenomenon: when observers are asked to detect two targets presented successively within a rapid serial visual presentation (RSVP) stream of nontarget items at a single location, attending to a briefly presented stimulus can substantially reduce awareness for a second stimulus (T2) presented shortly (within about half a second) after the first one (T1; Broadbent & Broadbent, 1987; Raymond, Shapiro, & Arnell, 1992; Reeves & Sperling, 1986). The AB reflects an impairment in a postperceptual stage of processing instead of suppression of perceptual processes (Vogel, Luck, & Shapiro, 1998). More evidence indicate that AB has been attributed to a temporary unavailability of task-critical processing resources because of limitations in the consolidation process (Chun & Potter, 1995; Jolicoeur & Dell'Acqua, 1998). Chun and Potter (1995) proposed a two-stage model to account for the AB in which stage 1 refers to the perceptual analysis of all inputs and stage 2 is the consolidation process with limited capacity (see also Jolicœur & Dell'Acqua, 1998; Shapiro, Raymond, & Arnell, 1997). Thus, by investigating how grouping modulates the attentional selection in time, it would provide evidence on the post-perceptual attentional mechanism that marks the transition between perceptual stimulus analysis and the subsequent storage of selected items in a capacity-limited working memory buffer (Vogel et al., 1998).

### 1.1.4 Grouping and visual working memory

Working memory (WM) is used to hold information actively in mind and to manipulate information in order to perform a cognitive task (Baddeley, 2000). A fundamental property of this memory system is that it is subject to severe storage capacity limitations. A common paradigm for studying visual working memory (VWM) is change detection (Luck & Vogel, 1997). In this paradigm, participants are asked to remember a set of objects in an initial memory display. After a retention interval, a test display is presented and participants have to indicate whether a change has occurred in one of the objects in the test as compared to the memory display. This paradigm made it possible to quantify VWM capacity. By recording event-related potentials (ERPs), a sustained posterior negativity, which is referred to as contralateral delay activity (CDA), is observed over the hemisphere that is contralateral to the memorized hemifield and persisted throughout the memory retention interval in the change detection task (Vogel & Machizawa, 2004). The CDA is found strongly correlated with individual differences in VWM capacity (Vogel & Machizawa, 2004, Vogel, McCollough, & Machizawa, 2005), thus providing an index of the items that are represented during the maintenance phase in VWM.

Two main theories of VWM capacity have been proposed, discrete slots and continuous resource theories (Luck, 2008b; Bays & Husain, 2008). Slot-based theories assume that a limited number of items ($K_{max}$) can be stored in VWM; if the number of items in the sensory input is greater than $K_{max}$, then $K_{max}$ of the items are stored in VWM and no information about the other items is stored in VWM (Luck & Vogel, 1997; Cowan, 2001; Luck & Vogel, 2013). In contrast to such slot accounts, resource models propose that VWM consists of a pool of resources that can be allocated flexibly to provide either a small number of high-quality representations or a larger number of low-quality representations (Bays & Husain, 2008).

While existing formal models of VWM mainly treat all items independently of each other (e.g., Luck & Vogel, 1997; Bays & Husain, 2008), relational scene properties such as perceptual grouping factors that potentially alter the basic structure of a scene might modulate the VWM capacity. Real-world scenes are typically complex and present structure that provides higher-order constraints on to-be-remembered items (for a review, see Brady, Konkle, & Alvarez, 2011; Brady & Tenenbaum, 2013; Conci & Müller, 2014). Working memory not only needs to represent the features of objects, but the more complex structure that goes beyond the level of individual items could also increase its storage capacity (Brady & Alvarez, 2011). This structure can, for example, be characterized as a hierarchy of object information, with global representations being dependent on the existence and arrangement of more elementary local parts. Therefore, observers might encode the "gist" of simple working memory displays in addition to information about specific items (their individual information). Results of visual search experiments on hierarchical patterns demonstrate that processing of the global level is faster than processing of the local level- the so-called global-precedence effect (Pomerantz, Sager, & Stoever, 1977; Rauschenberger & Yantis, 2001b; Deco & Heinke, 2007; Conci et al., 2007a, b). This global-precedence effect was also found with a hierarchical variant of the change detection task, in which detection of a global-object change precedes local-object changes of hierarchical shapes to a large extent (Nie, Müller, & Conci, 2017), challenging VWM models that propose a fixed number of objects that can be remembered regardless of the individual object structure.

The current thesis aims at observing the influences of object structure in VWM, that is, how object completion process affects the visual mnemonic representations. Although a large amount of studies showed that completion process is operated pre-attentively, representing completed objects has been suggested to rely on mental imagery (Nanay, 2010), which involves top-down process. On the other hand, there have been evidence showing that more cognitive resources are allocated during retention period when top-down demands increase (Sauseng, Hoppe, Klimesch, Gerloff, & Hummel, 2007; Sauseng et al., 2005) and that the storage capacity is rather determined by the "information load" associated with the to-be-memorized set of objects (Alvarez & Cavanagh, 2004; Luria, Sessa, Gotler, Jolicœur, & Dell'Acqua, 2010). It is possible that the maintenance of constructed complete objects in VWM requires additional attentional processes in order to keep object elements together as a coherent representation (see Pun, Emrich, Wilson, Stergiopoulos, & Ferber, 2012; Ewerdwalbesloh, Palva, Rösler, & Khader, 2016) and thus is severely restricted due to limited mnemonic resources available. To examine whether and how object completion is reflected in VWM capacity, it would provide a further understanding into the nature of the VWM capacity and the influences of grouping in the higher level of cognitive processing.

## 1.2 Aims of this thesis

The goal of this dissertation is to investigate the role of object integration and completion in attention and memory of humans. To approach this issue, classical psychophysical methods and EEG methods were employed. To tackle the mechanisms underlying grouping, we investigated how global attributes (of surface and contour completion) in Kanizsa figures modulate the sensitivity in detecting the location of a target dot. A subsequent study then examined the interaction between global object structure and attentional resources in temporal attention. Subsequently, we explicitly measured whether and how the working memory performance would be modulated by completion processes. In addition to the behavioral measures, the maintenance process were also tracked by means of the CDA with EEG measures.

To begin, in Chapter 2.1, a series of psychophysical experiments were performed to investigate complementary mechanisms underlying object completion, namely the contribution of contour interpolation and surface integration in perceiving a coherent Kanizsa figure. Although previous computational models have proposed separate processing of contour interpolation and surface filling-in, few empirical studies have attempted to investigate this issue directly. Therefore, in study 1, relative contour and surface information of the illusory figure was separated by gradually manipulating various aspects of grouping in the stimulus configurations. The detection sensitivity of the illusory region (and other variants such as illusory boundary or salient surface region) was measured using a dot-localization task while contrasting the relative impact of contour and surface completion mechanisms.

Subsequently, in Chapter 2.2, an experimental study is described that investigated how attention is allocated to grouped stimuli in time. Kanizsa figures were presented as targets in an RSVP stream of distractor stimuli. As described above, a large body of evidence is available on the spatial allocation of attention of Kanizsa figures. To complement these findings, this study investigated whether and how grouping structure in targets influences the profile of temporal attention. In this study, the crucial question concerned how the identification of the T2 configuration varies as a function of its grouping strength given the available, limited attentional resources. That is, by systematically varying the T1–T2 lag, we examined whether the grouping structure of T2 would modulate the AB effect.

Following this investigation of temporal attention in modal completion, Chapter 2.3 describes an experimental study that investigated whether amodal completion would influence the VWM performance. To this end, a change detection procedure was used to test whether ('amodal') completion of an object behind an occluder is reflected in VWM capacity. Observers were required to memorize either an array of simple objects (baseline), or displays that contain composite objects leading to amodally completed or uncompleted representations. Identical composite objects were presented but with different interpretations - either in terms of completed wholes (global or local completions) or as non-completed mosaic objects. Thus, any differences in the change detection performance can only be attributed to the difference in representations that may result from the amodal completion process rather than being attributable to an influence of perceptual shape discriminability.

Finally, in Chapter 2.4, related evidence from an EEG experiment is presented that examined the relationship between VWM storage and processes of object completion by combining behavioral measures with analysis of the CDA as an electrophysiological marker of VWM load. The difference between global and mosaic representations of identical composite objects in their maintenance demands would manifest in the CDA component.

# 2 Cumulative Thesis

This doctoral thesis consists of four individual studies: Two peer-reviewed and published articles (2.3 and 2.4) and two submitted manuscripts (2.1 and 2.2). The following chapter present these studies, each accompanied by a statement clarifying the contributions of the involved authors.

## 2.1 Study 1: Surface filling-in and contour interpolation contribute independently to Kanizsa figure formation

Contributions:

The author of this dissertation was primarily involved in designing and programming the experiment, collecting and analyzing the data, creating plots, interpreting the results and in writing of the manuscript.

Stefan Glasauer contributed to the data analysis and to the interpretation of the results. He also commented on the manuscript.

Hermann Müller helped with the interpretation of the results. He commented on and helped revising the manuscript.

Markus Conci conceived and supervised the project, participated in designing the experiments and interpreted the results. He also commented on and helped revising the manuscript.

# Surface filling-in and contour interpolation contribute independently to Kanizsa figure formation

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**Abstract**

To explore mechanisms of object integration, the present experiments examined how completion of illusory contours and surfaces modulates the sensitivity of localizing a target probe. Observers had to judge whether a briefly presented dot probe was located inside or outside the region demarcated by inducer elements that grouped to form variants of an illusory, Kanizsa-type figure. From the resulting psychometric functions, we determined observers' discrimination thresholds as a sensitivity measure. Experiment 1 showed that sensitivity was systematically modulated by the amount of surface and contour completion afforded by a given configuration. Experiments 2 and 3 presented stimulus variants that induced an (occluded) object without clearly defined bounding contours, which gave rise to a relative sensitivity increase for surface variations on their own. Experiments 4 and 5 were performed to rule out that these performance modulations are simply attributable to variable distances between critical local inducers, or to costs in processing an interrupted contour. Collectively, the findings provide evidence for a dissociation between surface and contour processing, supporting a model of object integration in which completion is instantiated by feedforward processing that independently renders surface filling-in and contour interpolation and a feedback loop that integrates these outputs into a complete whole.

## Introduction

Detecting the boundaries of objects is a fundamental task of early vision, so as to identify the available perceptual units, or objects, and segment these from other objects and from the background (Cornsweet, 1970; Marr, 1982). In many situations, object perception occurs despite degraded ambient luminance conditions, attesting to a remarkable capability of the visual system to integrate separate fragments into coherent wholes. This is illustrated in various examples of illusory figures (Kanizsa, 1955), where the presentation of 'pacman'-type inducer elements gives rise to the perception of illusory objects. For example, in Figure 1 (Kanizsa), a diamond-shape object is perceived to occlude neighboring parts of four circular elements, despite physically homogenous luminance across the diamond and background. Such a perceptual 'filling-in' of an object, accompanied by a concurrent brightness enhancement of the filled-in surface, is referred to as 'modal completion'.

It is commonly assumed that the mechanisms underlying such completion phenomena reflect the interpolation of the missing parts of the bounding contours and the filling-in of the surface of the enclosed area (Grossberg & Mingolla, 1985; Pessoa, Thompson, & Noë, 1998; Kogo, Strecha, Van Gool, & Wagemans, 2010). For instance, results from neurophysiological recordings suggest that the filling-in process, which generates the perception of an illusory surface, is associated with activations in the lateral occipital complex (LOC) and the fusiform gyrus (e.g., Stanley & Rubin, 2003; Bakar, Liu, Conci, Elliott, & Ioannides, 2008), while boundary completion is accomplished in both V1 and V2 (Lee & Nguyen, 2001; Von der Heydt, Peterhans, & Baurngartner, 1984) and to some extent also in the LOC (Shpaner, Stanley, Rubin, & Foxe, 2004; Murray, Imber, Javitt, & Foxe, 2006). Together, these findings suggest that separate regions in the ventral visual processing stream make distinct functional contributions to the perception of illusory figures (Seghier & Vuilleumier, 2006, for a review). The present study aimed at determining the relative contributions of such contour and surface completion mechanisms in forming the percept of an illusory figure.

Recent behavioral studies have used the visual search paradigm to systematically examine the role of surface and contour processing in variations of Kanizsa figures. To this end, configurations were generated that either presented an illusory Kanizsa figure (Figure 1, Kanizsa), or a symmetric configuration that does not induce an illusory shape (Figure 1, Baseline). Additional configurations induced 'partial' groupings, that is, either a partial illusory contour (Figure 1, Contour) or a partial contour-plus-surface arrangement (Figure 1, Shape). Conci, Müller, and Elliott (2007a) presented such configurations in a visual search task to investigate how surface and contour grouping in distractors would modulate detection of a Kanizsa target shape. They found that the partial surface, but not the presence of contours in distractors, modulates the efficiency with which a Kanizsa target square is detected (see also Conci, Gramann, Müller, & Elliott, 2006; Nie, Maurer, Müller, & Conci, 2016). This suggests that the selection of an illusory figure primarily relies on processes of surface filling-in. In this view, visual search with illusory figures is largely guided by a crude specification of a closed target shape, without requirement to compute the exact contours of the respective objects. However, the type of search task used in this study (see Davis & Driver. 1994) likely only requires a relatively broad tuning of attention to a target (Kanizsa) shape, so that it might, in fact, underestimate the role of contour interpolation. By contrast, studies of neuropsychological patients with visual neglect (Vuilleumier & Landis, 1998; Vuilleumier, Valenza, & Landis, 2001) indicate that contour completion can also determine attentional selection, thereby reducing extinction behavior. This suggests that both the filling-in of surfaces and the interpolation of the bounding contours might be accomplished at early stages of visual processing, thus guiding attention to potential target locations.

To directly measure illusory figure completion, Stanley and Rubin (2003) used a psychophysical method that allows perceptual sensitivity to be determined in a dot-localization task (see also Guttman & Kellman, 2004). The task involved the localization of a dot probe, which was presented briefly near a presumed illusory edge in a Kanizsa figure configuration. Observers were asked to decide whether the presented dot appeared inside or outside the region demarcated by the Kanizsa figure. Performance in this task was then used to determine psychometric functions, with their slope parameter characterizing the dot-localization sensitivity. Stanley and Rubin showed that the sensitivity in localizing the dot was significantly higher for an illusory (Kanizsa) figure than for a configuration that presented a closed region without concurrent illusory contour. Using a roughly similar method (but without explicitly quantifying sensitivity), it has also been shown that detection of a target dot is more efficient inside an illusory edge of a Kanizsa figure than outside (Ricciardelli, Bonfiglioli, Nicoletti, & Umiltá, 2001). Together, these findings suggest that the perceptual sensitivity in the dot-localization task can provide an indirect measure of grouping strength, with the Kanizsa figure being associated with a higher sensitivity than a comparable configuration without illusory object.

To further investigate how contours and surfaces influence the completion of Kanizsa figures, the current study presented configurations that allow for a dissociation of the respective surface and contour portions of a grouped figure (see Conci et al., 2006; 2007a) using the dot-localization task (Stanley & Rubin, 2003) in a series of psychophysical experiments. The configurations that were presented in the experiments were characterized by a graded amount of surface and contour in variants of Kanizsa figure configurations (see Figure 1): the Kanizsa diamond induces a complete illusory figure (Figure 1, Kanizsa), the 'Shape' configuration provides partial surface and contour information (Figure 1, Shape), and the 'Contour' configuration induces only a partial illusory contour (Figure 1, Contour); the 'Baseline' arrangement, by contrast, presents no grouped object (i.e., no illusory figure) while consisting of similar inducer elements and a symmetric arrangement (Figure 1, Baseline). The efficiency of illusory figure completion was measured by quantifying the discrimination in the inside/outside dot-localization task by determining psychometric functions for these four types of configuration. The discrimination threshold of the psychometric functions was then used as a measure of the perceptual sensitivity. Thus, comparing the perceptual sensitivity among the Kanizsa, Shape, Contour, and Baseline conditions permitted us to effectively assess how contour interpolation and surface filling-in processes contribute to the completion of an illusory figure.

**Experiment 1**

Experiment 1 was performed to measure the contribution of surface and contour completions in illusory figure perception, by employing a dot-localization task in which observers had to decide whether a target dot was located inside or outside a region demarcated by the inducer elements of a Kanizsa-type configuration (see also Stanley & Rubin, 2003, and Figure 1 for possible types of configuration). The discrimination threshold of dot-localization performance estimated from the psychometric function was taken as a measure of the perceptual sensitivity for a given configuration, thus permitting us to assess how surface filling-in and contour interpolation modulate the perceptual sensitivity.

### *Method*

***Participants.*** Twelve right-handed volunteers (8 men; mean age: 23.42 ± 1.98 years) with normal or corrected-to-normal visual acuity participated in the experiment for payment of €8.00 per hour. All participants provided written informed consent, and the experimental procedure was approved by the ethics committee of the Department of Psychology, Ludwig-Maximilians-Universität München. The sample size was determined on the basis of previous, comparable studies (e.g., Stanley & Rubin, 2003), aiming for 80% power to detect a relatively large effect size ($f$=.4; cf. Cohen, 1988) when using a repeated-measures ANOVA (within-factors, 4 conditions) with an alpha level of .05. Power estimates were computed using G*Power (Erdfelder, Faul, & Buchner, 1996). It should be noted that studies, which compute psychometric functions tend to conventionally test rather small samples, often with less than ten observers (e.g. Shi & Nijhawan, 2008; Hickok, Farahbod, & Saberi, 2015), but at the same time seek to thoroughly characterize performance for each subject using many trials with rather fine-grained measurement steps in order to determine a rather precise sensitivity estimate.

***Apparatus and Stimuli.*** The experiment was conducted in a sound-attenuated room that was dimly lit with indirect, incandescent lighting. Stimuli were generated with an IBM-PC compatible computer using Matlab routines and Psychophysics Toolbox extensions (Brainard, 1997; Pelli, 1997), and were presented in light gray (1.83 cd/m$^2$) against a black (0.02 cd/m$^2$) background at the center of a 17-inch monitor screen (1024×768 pixels screen resolution, 85-Hz refresh rate). There were four types of experimental stimuli (see Figure 1): (1) a Kanizsa-type diamond shape (Kanizsa), (2) a shape configuration that depicted partial contour and surface completions (Shape), (3) a configuration that only induced an illusory contour without an associated surface (Contour), and (4) a control configuration that consisted of four outward-facing 'pacman' inducers, revealing a symmetric arrangement but without any emerging shape (Baseline). Each pacman inducer subtended a visual angle of 1.1°. The radius of the illusory diamond shape in the Kanizsa figure configuration was 3.7° of visual angle. The 'support ratio' (Banton & Levi, 1992), that is, the ratio between the luminance-defined portion and the completed illusory contour, was 0.4.

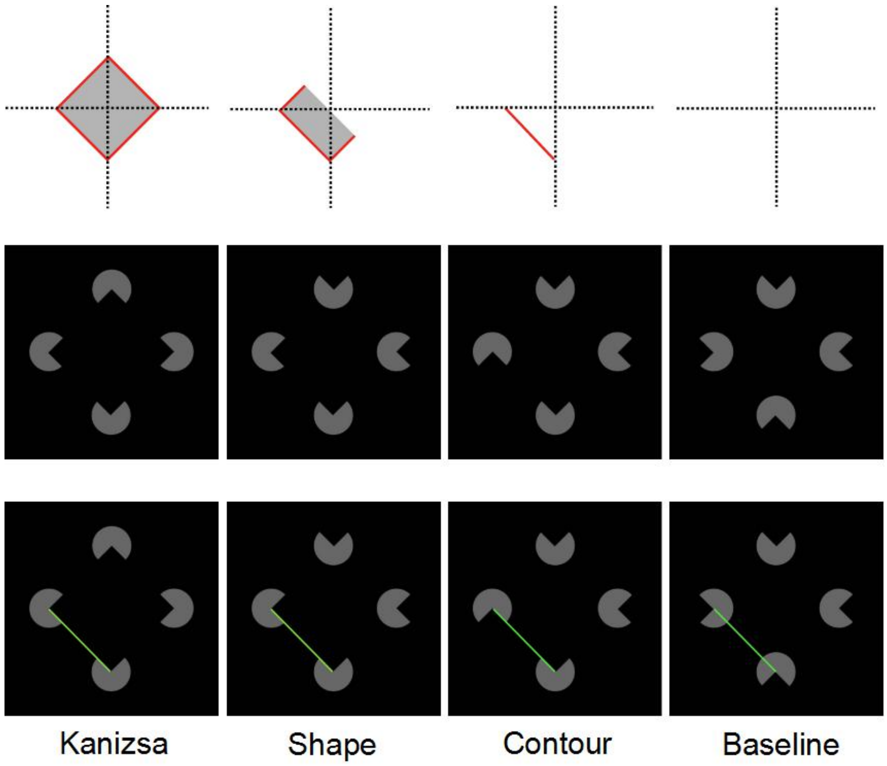
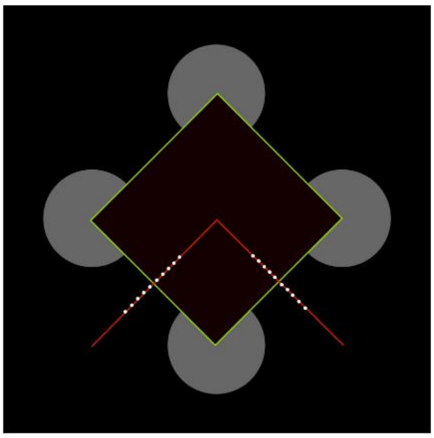



**Figure 1.** Examples of the modal completion stimuli used in Experiment 1. An example of each possible configuration (Kanizsa, Shape, Contour, Baseline) is depicted in the middle panels. In the examples, partial groupings in the Shape and Contour stimuli are induced in the bottom-left quadrants of a given configuration. The top panels illustrate the corresponding emergent grouping, displaying the respective surface (gray) and contour (red) completion. In addition, the bottom panels illustrate the presumed boundary of the inner region for a given configuration (green line) when the dot appeared on the left side. Note that the green line was not shown in the actual experiment, but only serves to illustrate the respective borders. See text for further details.

***Procedure.*** Observers performed a dot-localization task. Each trial started with the presentation of a central fixation cross for 250 ms, followed by a 750-ms pre-cue display that presented four disks in a diamond arrangement around the central fixation cross. Next, one of the four configuration conditions (Kanizsa, Shape, Contour or Baseline) was briefly presented for 150 ms, after which a (target) dot probe (with a diameter of 8.3 arc-min) was added to the display and presented for another 100 ms near the bottom left or right illusory edge of a given pacman configuration. The dot probe appeared randomly at one of ten equidistant locations within a range of -53 to 53 arc-min along the midline perpendicular to the bottom left or right border of the illusory figure (see Figure 2A for possible dot locations). Observers indicated whether the dot probe was located inside or outside of the region enclosed by the inducers, by pressing the left or the right button on a computer mouse, respectively. To ensure that observers correctly performed the task, detailed instructions were provided (https://osf.io/3ydju/), which also included illustrations of the correct boundary that determines the inner region of the configuration (see green lines in Figure 1, bottom panels). Note that the boundary of a given configuration was always located at the very same position on the screen for all types of configuration. On a given trial, observers were instructed to fixate the central fixation cross. The relatively short duration of the dot probe (100 ms) ensured that observers could not make eye movements towards it. An example trial sequence is shown in Figure 2B.

A.



B.

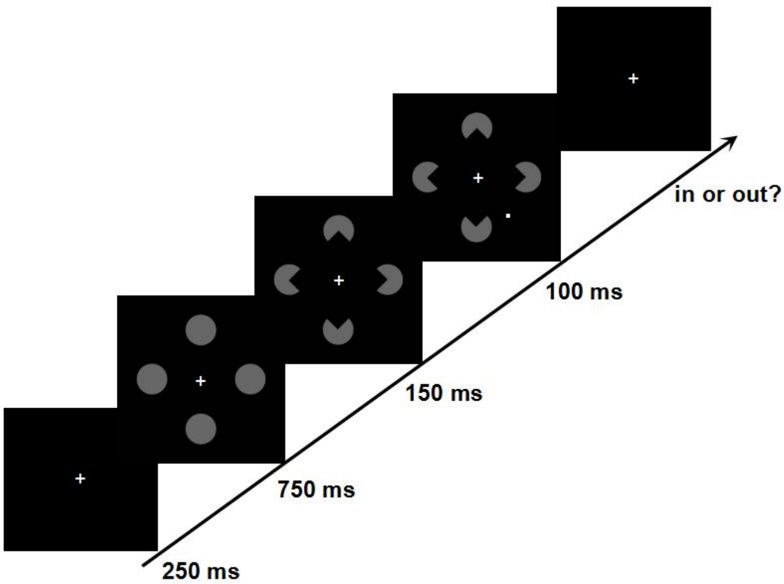


**Figure 2**. (A) Illustration of possible dot locations in the experiments. The dot probe appeared at one of ten equidistant locations along the midline (red) perpendicular to the bottom left or right border (green) of the illusory figure. Note that the red and green lines were not shown in the actual experiment; they only serve to illustrate the stimulus layout. (B) Example trial sequence in the dot localization task. Subsequent to a pre-cue display (750 ms), a configuration display (either Kanizsa, Shape, Contour, or Baseline) was briefly presented (150 ms), after which a dot probe was added and presented for another 100 ms. In the example, the dot is presented near the bottom right boundary of the enclosed region. Observers were instructed to report whether the dot appeared inside or outside the enclosed illusory region. In the example, the correct response would be 'out'.

Every participant completed 8 blocks of 100 trials each, resulting in 800 trials in total. Every block presented one of the four configurations (Kanizsa, Shape, Contour, and Baseline) with the dot appearing either in the lower left or the lower right quadrant of the stimulus in separate blocks, with randomized block order across participants. Note that we probed the lower left and right quadrants of the display because the lower hemifield has been shown to produce a stronger percept of illusory figures than the upper hemifield (Rubin, Nakayama, & Shapley, 1996). In each block, a given configuration was presented with ten possible dot locations in a given quadrant across ten repetitions. For the analysis, the data from the left and right dot-presentation quadrants were collapsed. Before the experiment, every participant was acquainted with the task in a block of 16 practice trials.

The fraction of 'out' responses was plotted against the relative dot position. These data were fitted with a psychometric function $0.5\times[1 + \gamma\times \mathit{tanh}(0.745(x\text{-}\beta)/\alpha)]$, where $\alpha$ is the discrimination threshold defined as stimulus increment from $\beta$ (the Point of Subjective Equivalence, PSE) to reach 82% performance (see Stanley & Rubin 2003), and $\gamma$ reflects the performance range. Note that the discrimination threshold $\alpha$ is inversely related to the slope of the psychometric function (the slope at the PSE is $0.3725/\alpha$) and thus gives an indication of the precision, while the PSE $\beta$ defines the accuracy.

### *Results*

The results of Experiment 1 are depicted in Figure 3A. The psychometric curves show the across-observer average fraction of 'out' responses as a function of dot position (upper panel). The numbers on the x-axis denote the relative distances from the objective boundary of the configuration, with positive values corresponding to “outside” dot locations and negative values to “inside” locations (see Figure 3A; a value of zero would correspond to the location of the boundary). The corresponding slopes of the curves provide an estimate of the sharpness of the perceived illusory figure. We defined the discrimination threshold as the dot displacement needed to shift responses from 50% to 82% ‘out’ (see Methods above). The lower panel in Figure 3A displays the corresponding mean discrimination thresholds (α) across observers in the four conditions. To determine whether there were differences in the discrimination threshold of the psychometric functions across configurations, we performed a repeated-measures ANOVA with the factor configuration (Kanizsa, Shape, Contour, Baseline). We additionally report the estimated Bayes factors ($BF_{10}$) as revealed by comparable Bayesian statistics using JASP (Love et al., 2015). The Bayes factor provides the ratio with which the alternative hypothesis is favored over the null hypothesis (i.e., larger BFs argue in favor of the alternative hypothesis with values below 1 supporting the null hypothesis while values above 3 would indicate moderate -, and values above 10 strong evidence in favor of the alternative hypothesis; see Jeffreys, 1961; Kass & Raftery, 1995).

This analysis yielded a significant main effect, $F(3, 33) = 44.92$, $p < .0001$, $\eta_p^2 = .80$, 90% confidence interval, or CI [.67, .85], $BF_{10}$ =6.25e+11. For the post-hoc comparisons, given that such repeated testing increases the chance of obtaining a significant effect, a Bonferroni correction was applied (Neter & Wasserman, 1974). Thresholds were lower in the Kanizsa condition ($M = 4.53$) compared to all other conditions (Shape vs. Kanizsa: $t(11) = 3.91$, $p = .015$, $d_z = 1.13$, 95% CI [.38, 1.84], $BF_{10} = 18.83$; Contour vs. Kanizsa: $t(11) = 6.45$, $p < .0001$, $d_z = 1.86$, 95% CI [.89, 2.80], $BF_{10} = 553.01$; Baseline vs. Kanizsa: $t(11) = 7.99$, $p < .0001$, $d_z = 2.31$, 95% CI [1.19, 3.40], $BF_{10} = 3109.71$). The Shape threshold ($M = 6.17$) was lower than the Contour and Baseline thresholds (Contour vs. Shape: $t(11) = 6.01$, $p = .001$, $d_z = 1.73$, 95% CI [.81, 2.63], $BF_{10}$ =320.32; Baseline vs. Shape: $t(11) = 7.31$, $p < .0001$, $d_z = 2.11$, 95% CI [1.06, 3.13], $BF_{10}$ =1489.78). Finally, the threshold for the Contour ($M = 9.95$) was lower than that for the Baseline ($M = 14.56$; $t(11) = -4.32$, $p =.007$, $d_z = -1.25$, 95% CI [-2.00, -.47], $BF_{10} = 33.86$).

According to Figure 3A (upper panel), the Point of Subjective Equivalence (PSE, 50%) appeared to be shifted leftwards from the objective contour location (‘0’), in particular for the Kanizsa condition. We therefore determined the PSE from the psychometric function (β). The deviation from the objective contour location was tested with a series of one-sample t-tests (2-tailed). Among the four configurations, only the Kanizsa figure showed a significant deviation from objective contour location ($M = -3.13$), $t(11) = -3.10$, $p = .01$, $d_z = -.90$, 95% CI [-1.56, -.21], $BF_{10} = 5.88$ (all other conditions, $ts(11) < .74$, $ps > .48$, all $d_z < .21$, all $BF_{10} < 0.36$). A potential interpretation of this deviation for the Kanizsa diamond might be that observers perceive the illusory contour as being curved towards the inside. Note that a comparable result was also obtained in Experiments 3–5 for the Kanizsa condition [$ts(11) < -3.01$, $ps < .01$, all $d_z < -.87$, all $BF_{10} > 5.15$].

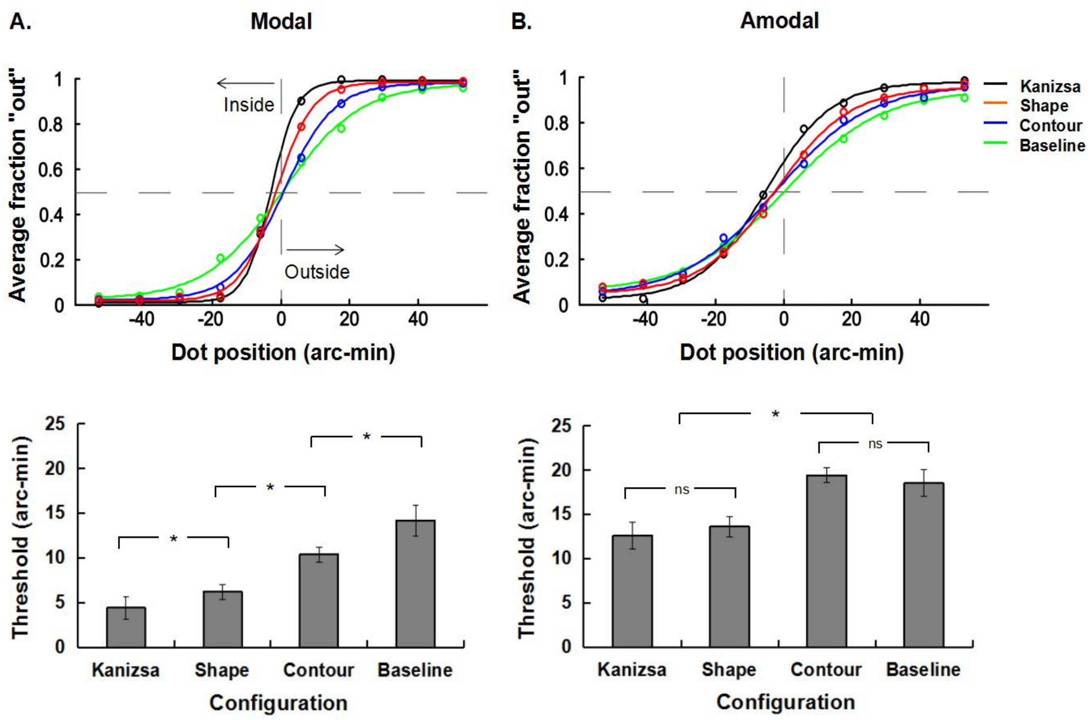



**Figure 3.** Upper panel: Psychometric curves in the dot-localization task, across observer means, in Experiment 1 (A) and Experiment 2 (B). In the graphs shown, the fraction of 'out' responses is plotted against dot position, for the Kanizsa, Shape, Contour, and Baseline conditions in the modal (A) and amodal (B) configurations. Steeper slopes indicate perception of a sharper illusory figure. Note that positive values on the x-axis indicate "outside" dot-locations and negative values "inside" locations. Lower panel: Corresponding mean discrimination thresholds in the Kanizsa, Shape, Contour, and Baseline conditions in Experiment 1 (A) and Experiment 2 (B). Error bars denote 95% within-subject confidence intervals. *$p < .05$, Bonferroni corrected.

***Discussion***

The discrimination threshold of the psychometric function as derived from the dot-localization performance provides an estimate of the perceptual sensitivity, that is, the ‘sharpness’ of the perceived illusory figure. Experiment 1 characterized the effect of surface and contour information on the discrimination thresholds as determined from the psychometric functions. Our results suggest overall a high precision in measuring the perceptual sensitivity with the current procedure (all $\eta_p^2 > .14$, $|d| > .8$; $BF_{10} > 10$; see Cohen, 1988; Jeffreys, 1961). The threshold derived from these measurements revealed to be lowest for Kanizsa figures, followed by Shape and Contour configurations, indicating that the perceptual sensitivity is modulated by the amount of surface information present in the configuration, with higher sensitivity – as indicated by a decreased threshold and a steeper slope in the psychometric function – with more surface information. In addition, we also observed that contour information impacts the perception of the illusory shape, with a significantly decreased threshold for Contour as compared to Baseline configurations, illustrating that contours on their own can support efficient dot localization (see also Conci et al., 2009). This indicates that both surface and contour completions strengthen the perception of the illusory figure.

An additional analysis showed that the Kanizsa figure exhibited a significant deviation from the objective contour location (when assuming that the illusory contour renders a straight, linear boundary). This result is consistent with the view that the illusory contour is actually perceived as being somewhat curved towards the inside. Using Kanizsa triangles as test stimuli, Gintner, Aparajeya, Leymarie, and Kovács (2016) recently observed a comparable pattern of contour curvature towards the inside – a pattern in line with the current finding, indicating that the visual system ultimately represents illusory contours with less precision and accuracy than comparable luminance-defined contours (see also Guttman & Kellman, 2004). While the contours of the Kanizsa diamond were thus perceived as slightly curved, the same analysis of the PSE for the Baseline (and Shape as well as Contour conditions) revealed no reliable deviation from the objective contour location. This shows that participants did follow the instructions and responded based on the boundary at the same location in all configurations (i.e., as illustrated by the green lines in Figure 1).

**Experiment 2**

Experiment 1 revealed a graded reduction of the discrimination threshold from Baseline through Contour and Shape configurations to the Kanizsa diamond. A potential explanation of this pattern might be that the computation of both the illusory contours and the surface contributed to the change in precision. Alternatively, it might be the contour alone which leads to a performance difference, with stronger contour perception in the Kanizsa and Shape configurations compared to the Contour condition (i.e., with the object's surface enhancing the strength of the contour and thereby facilitating performance). To decide between these alternatives, Experiments 2 and 3 were performed to determine whether dot detection performance would also be modulated by other forms of completion that provide a comparable amount of surface filling-in, but without giving rise to a corresponding (illusory) contour.

For instance, besides modal completion, which was tested in Experiment 1, another, related grouping phenomenon is referred to as 'amodal completion', which occurs when an interpolated figure is perceived as lying behind an occluding object (see Figure 4A; Michotte, Thines, & Crabbe, 1964/1991; Kanizsa, 1979; see also Chen, Müller & Conci, 2016; Chen, Töllner, Müller, & Conci, 2017). Figure 1 provides a typical example of modal completion: a Kanizsa diamond that induces a bright surface with illusory contours. In comparison, in the example depicted in Figure 4A, an integrated diamond is perceived as well, but it appears to be completed behind the four circular apertures. Thus, in this case, the diamond shape is completed behind the occluding region, and as a result, the illusory contour is not directly visible (see illustration in Figure 4A, and Michotte et al., 1964/1991). Thus, in the configurations in Figure 4B, surface completion remains to connect disparate parts of the figures (e.g., in the Kanizsa and Shape conditions), but there is no crisp boundary forming an illusory contour (e.g. in all configurations presented in Figure 4B).

Experiment 2 used a similar paradigm to that described for Experiment 1 and investigated how the dot-localization sensitivity is affected by amodal completion (as opposed to modal completion in Experiment 1), that is, when the illusory contours are not visible due to partial occlusion. If surface processing contributes to our performance measure and is dissociable from the completion of (illusory) contours, then perceptual sensitivity would be expected to be modulated by surfaces even when no precise bounding contour is available.

***Method***

Experiment 2 was basically identical to Experiment 1, with the following differences: 12 right-handed paid volunteers (7 men; mean age: 23.5 ± 2.15 years; normal or corrected-to-normal vision) participated in the experiment. Stimuli in Experiment 2 were designed to induce amodal completion. The stimulus arrangements were identical to those revealing modal completion in Experiment 1, except that a gray outline circle was added to surround each pacman inducer (line thickness: 9 arc-min; see Figure 4B).

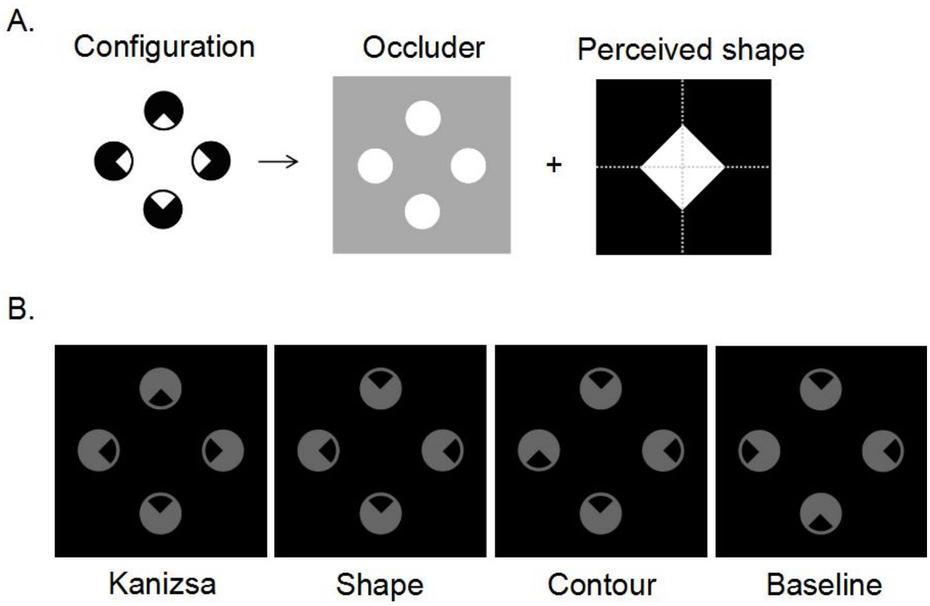



**Figure 4.** (A) An example configuration that leads to amodal completion. In the configuration, a diamond shape is perceived as lying behind an occluding surface. (B) Examples of the amodal completion stimuli used in Experiment 2. Partial groupings in the Shape and Contour stimuli are induced in the bottom-left quadrants of a given configuration.

***Results***

The upper panel in Figure 3B displays the psychometric curves (averaged across observers) as a function of dot position, separately for the different configuration conditions. In addition, the lower panel of Figure 3B shows the corresponding mean discrimination thresholds. A repeated-measures ANOVA with the factor configuration (Kanizsa, Shape, Contour, Baseline)[1] again revealed a significant

[1] It should be noted that a Kanizsa figure is typically an example of modal completion – so that the term "Kanizsa", in a strict sense, would only be appropriate when describing the diamond stimulus as used in Experiment 1. However, for the sake of consistency (i.e., for providing a coherent terminology when describing our experimental manipulations), we nevertheless used comparable labels for our conditions throughout all experiments in this study.

effect, $F(3, 33) = 20.76$, $p < .0001$, $\eta_p^2 = .65$, 90% CI [.44, .73], $BF_{10} = 9.43e+4$. The thresholds were lower for Kanizsa ($M = 12.63$) and Shape ($M = 13.62$) than for Contour ($M = 19.44$) and Baseline ($M = 18.55$) configurations (Contour vs. Kanizsa: $t(11) = 6.53$, $p < .0001$, $d_z = 1.88$, 95% CI [.91, 2.83], $BF_{10} = 603.42$; Baseline vs. Kanizsa: $t(11) = 4.44$, $p = .006$, $d_z = 1.28$, 95% CI [.49, 2.04], $BF_{10} = 40.29$; Contour vs. Shape: $t(11) = 9.01$, $p < .0001$, $d_z = 2.60$, 95% CI [1.38, 3.80], $BF_{10} = 8.64e+3$; Baseline vs. Shape: $t(11) = 4.33$, $p = .007$, $d_z = 1.25$, 95% CI [.47, 2.00], $BF_{10} = 34.27$). There were no significant threshold differences between Kanizsa and Shape, $t(11) = .87$, $p = 1.00$, $d_z = .25$, 95% CI [-.33, .82], $BF_{10} = 0.40$, or between Contour and Baseline configurations, $t(11) = .92$, $p = 1.00$, $d_z = .27$, 95% CI [-.32, .84], $BF_{10} = 0.41$.

A further analysis then compared all configurations across Experiments 1 and 2. To this end, we performed a mixed-design ANOVA with the within-subjects factor configuration and the between-subjects factor experiment. This analysis revealed a main effect of configuration, $F(3, 66) = 57.28$, $p < .0001$, $\eta_p^2 = .72$, 90% CI [.61, .77], $BF_{10} = 5.03e+13$, with lower thresholds for Kanizsa and Shape than for either Contour or Baseline configurations, $t$s(11) > 7.66, $p$s < .0001, all $d_z > 1.56$, all $BF_{10} > 1.66e+5$; and a main effect of experiment, $F(1, 22) = 18.32$, $p < .0001$, $\eta_p^2 = .45$, 90% CI [.18, .62], $BF_{10} = 86.52$, with higher thresholds in Experiment 2 ($M = 16.06$) than in Experiment 1 ($M = 8.80$). The interaction between configuration and experiment was also significant, $F(3, 66) = 5.43$, $p = .002$, $\eta_p^2 = .20$, 90% CI [.05, .31], $BF_{10} = 14.45$: there was no significant difference in thresholds between experiments for Baseline configurations, $t(11) = 1.91$, $p = .07$, $d = .78$, 95% CI [-.06, 1.61], $BF_{10} = 1.34$, but thresholds were overall higher in Experiment 2 than in Experiment 1 for Kanizsa, Shape, and Contour configurations, $ts(11) > 3.73$, $p$s < .001, all $d > 1.52$, all $BF_{10} > 26.95$.

### ***Discussion***

Experiment 2 presented amodal completion stimuli, where the illusory figure is perceived as being partially occluded. The results of Experiment 2 suggest that surface completion influences performance despite the occlusion, as amodal variants of Kanizsa and Shape configurations still exhibited a higher dot-localization sensitivity than corresponding Contour and Baseline stimuli. It should be noted in this regard that there was no significant difference in sensitivity when comparing the amodally completed contour and baseline configurations (the threshold for Contour was numerically even higher than for Baseline). This confirms that an illusory contour is not effectively completed across an occluder, but nevertheless an occluded region still modulates detection performance.

The occluded configurations in Experiment 2 led to an overall decreased sensitivity of dot localization for stimuli that induce an illusory region (Kanizsa, Shape, and Contour configurations), as compared to Experiment 1 with comparable modal-completion stimuli. However, no significant difference between the two experiments was found in the Baseline, suggesting that the performance reduction occurred because of the increased difficulty in processing the occluded object, but not because of a potential difference in perceptual complexity of the configurations that may have resulted from the addition of the outline circles.

To further substantiate that the non-significant differences between Kanizsa and Shape ($d_z$ = .25), and between Contour and Baseline configurations ($d_z$ = .27) were not due to a lack of statistical power, we conducted a second post-hoc power analysis, again setting power to 80% and the alpha level to .05 (two-tailed). In Experiment 1, the effect size of the smallest numerical contrast (i.e. between Kanizsa and Shape conditions) was 1.13, thus, revealing a large effect (cf. Cohen, 1988). The power analysis in fact showed that our current sample size would be sufficient to detect such an effect size. It is therefore unlikely that our non-significant effects can be attributed to a limitation in sample size. Moreover, an additional estimation of the Bayes factor for these non-significant differences revealed that both the comparisons between Kanizsa and Shape ($BF_{10}$ = 0.40) and between Contour and Baseline ($BF_{10}$ = 0.41) were clearly in favor of the null hypothesis.

**Experiment 3**

Experiment 2 provided clear evidence for a surface-based modulation of performance even though no illusory contour was visible in the presented (amodal) configurations. It could be argued, however, that amodal completion (i.e., the grouping of an object behind an occluder) is, in crucial ways, different from modal completion (e.g., in “standard” Kanizsa figures as tested in Experiment 1; see Murray, Foxe, Javitt, & Foxe, 2004). Experiment 3 was therefore performed to further investigate whether a performance modulation for surface-defined groupings (without a concurrent illusory contour) could also be demonstrated in cases of modal completion. To this end, configurations were presented with smoothed pacman inducers, which, in previous studies, have been shown to reveal surface completion, that is, affording selection based on a “salient region” (Shipley & Kellman, 1990; Stanley & Rubin, 2003), without a corresponding illusory contour (see Figure 5). If dot-localization sensitivity is modulated by the presence of a salient region alone, then surface filling-in and contour interpolation might be considered separate mechanisms that contribute to the completion of an illusory figure in both variants of modal and amodal completion.

### *Method*

Experiment 3 was again basically identical to Experiments 1 and 2, with the following differences: 12 right-handed paid volunteers (5 men; mean age: 25.92 ± 5.57 years; normal or corrected-to-normal vision) participated in the experiment. There were two possible stimulus configurations: Kanizsa configurations, consisting of a salient, central object, were compared to Baseline configurations (i.e., stimulus arrangements that do not give rise to any emerging shape). In addition, these two types of configuration could be presented with two types of inducers, or edges (“sharp” and “smoothed”), resulting in four possible conditions: stimuli with “sharp” edges were essentially identical to the configurations presented in Experiment 1 (see Figure 5), whereas the sharp corners of the inducer shapes were eliminated in configurations with “smoothed” edges. In the smoothed variant of the Kanizsa configuration, this change of the inducers created the impression of an enclosed “salient region”, but without a crisp bounding contour (Shipley & Kellman, 1990; Stanley & Rubin, 2003; see Figure 5). Smoothed inducers were generated by manually tracing the outlines of the inducers to eliminate their sharp corners and then rotating each inducer by 10 degrees clockwise to eliminate the alignment of the straight parts of the edges. This procedure was similar to previous studies, which also used smoothed inducers (e.g., Stanley & Rubin, 2003).

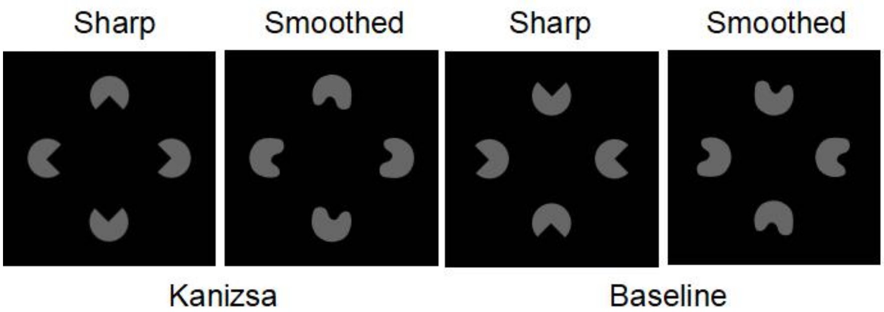



**Figure 5.** Example stimuli used in Experiment 3. The Kanizsa and Baseline configurations with sharp edges are the same as in Experiment 1. In the Kanizsa configuration with smoothed edges, the arrangement of the inducing elements creates an impression of an enclosed "salient" region, but this region is not bounded by crisp illusory contours.

### *Results*

Figure 6 presents the psychometric curves (top) and the corresponding mean discrimination thresholds (bottom) for the different conditions in Experiment 3 (upper and lower panels, respectively). A repeated-measures ANOVA with the factors configuration (Kanizsa, Baseline) and edge (sharp, smoothed) on the discrimination thresholds revealed a significant main effect of configuration, $F(1, 11) = 40.10$, $p < .0001$, $\eta_p^2 = .79$, 90% CI [.49, .86], $BF_{10} = 6.59e+4$: thresholds were lower for Kanizsa ($M = 8.35$) than for Baseline configurations ($M = 16.05$). The main effect of edge was not significant, $F\,(1, 11) = 3.91$, $p = .07$, $\eta_p^2 = .26$, 90% CI [0, .52], $BF_{10} = .54$, and there was also no interaction effect, $F\,(1, 11) = 1.47$, $p = .25$, $\eta_p^2 = .12$, 90% CI [0, .39], $BF_{10} = .68$. However, despite of the non-significant interaction, paired-t tests still revealed a significantly lower threshold for the Kanizsa configuration with sharp edges than that with smoothed edges, $t(11) = -2.74$, $p = .019$, $d_z = -.79$, 95% CI [-1.43, -.12], $BF_{10} = 3.49$, while there was no difference between the two edge types for Baseline configurations, $t(11) = -.30$, $p = .77$, $d_z = -.09$, 95% CI [-.65, .48], $BF_{10} = .30$.

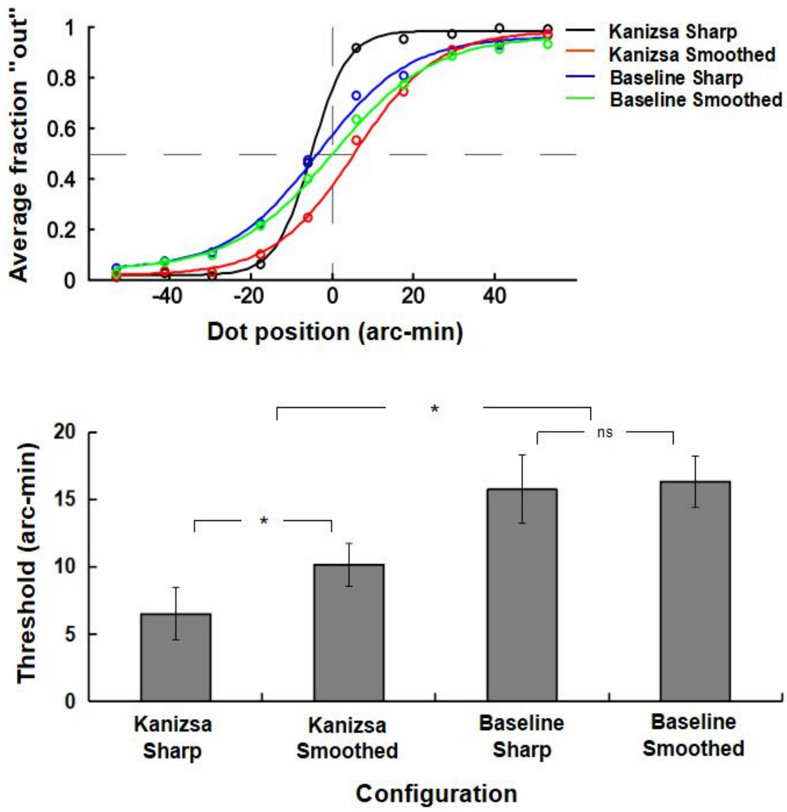



**Figure 6.** Upper panel: Psychometric curves in the dot-localization task, across observer means, in Experiment 3. The fraction of ‘out’ responses is plotted against dot position, for the Kanizsa and Baseline configurations with sharp or smoothed edges. Lower panel: Mean discrimination thresholds in the Kanizsa and Baseline configurations with sharp/smoothed edges in Experiment 3. Error bars denote 95% within-subject confidence intervals. *$p < .05$, Bonferroni corrected.

***Discussion***

Experiment 3 compared performance for Kanizsa and Baseline configurations with sharp and smoothed edges. In the Kanizsa configuration with smoothed edges, surface completion mechanisms typically render the impression of a closed, “salient region” that is perceived (even) without concurrent illusory contours (Stanley & Rubin, 2003). Accordingly, the results of Experiment 3 suggest that salient-region computations influence dot-localization performance even in the absence of illusory contours – as evidenced by a consistently higher sensitivity for Kanizsa as compared to Baseline configurations, independently of the type of edge (sharp or smoothed). Although the interaction was non-significant, there was still a significant difference between Kanizsa configurations with sharp and smoothed edges, consistent with Stanley and Rubin (2003) who used comparable stimuli and the same task. This pattern suggests that both surface information and contour processing contributed to the observed modulation of dot-localization sensitivity. For the Baseline condition, by contrast, there was no difference between configurations with smoothed and sharp edges, that is, the subtle physical difference between the two types of inducers alone did not impact the basic level of performance.

Together, Experiments 2 and 3 show that surface filling-in can facilitate the perception of modally and amodally completed configurations, over and above any contribution from the interpolation of illusory contours (e.g., as revealed in Experiment 1). This indicates that illusory contours and salient surfaces are computed by separate mechanisms that do not necessarily depend on each other.

## Experiment 4

Across Experiments 1 to 3, an increased sensitivity was revealed for the Kanizsa figure as compared to configurations that do not induce a comparable illusory shape (e.g., the Baseline configuration). As outlined above, this difference can be explained by grouping mechanisms, according to which localization of the dot is more accurate when an illusory shape allows estimation of the precise position of the target dot in relation to the illusory figure. However, a potential alternative account may simply be that the advantage for the Kanizsa figure results from the shorter spatial distance between the edges of the two inward-facing pacmen in the Kanizsa figure, as compared to a somewhat larger distance between edges in the two outward-facing pacmen in the Baseline condition (see Figure 7A, left and middle panels for an illustration). Note that this latter account would attribute the observed differences in performance primarily to the distance between the edges of a configuration, rather than to the completion of an illusory figure. To exclude this potential confound, in Experiment 4, we equated the distances between the edges of two neighboring pacmen using rectangular variants of the Kanizsa figure and the Baseline configuration of Experiment 1.

### *Method*

Experiment 4 was largely identical to Experiment 1, with the following differences: 12 right-handed paid volunteers (7 men; mean age: 25 ± 3.10 years; normal or corrected-to-normal vision) participated in the experiment. There were again four possible stimulus configurations in the experiment: The ‘Smaller’ Kanizsa and Baseline configurations were identical to the ones presented previously in Experiment 1. Two additional configurations presented larger, rectangular stimulus arrangements (the “Larger Kanizsa” and “Larger Baseline” configurations). For the larger Kanizsa configuration, the distance between the edges of the two pacmen on the side where the target dot appeared was the same as that of the original Baseline configuration in Experiment 1 (see Figure 7A, right and middle panels, respectively). The support ratio for the larger Kanizsa diamond was 0.29. The larger Baseline configuration was identical to the Baseline condition (also presenting no illusory object), but with the pacman inducers placed at same distances as for the larger Kanizsa stimulus configuration. These additional larger variants of the configurations permitted assessment of the effect of contour length on performance, while keeping the distance between the central fixation cross and the dot constant (for examples of the actual stimuli, see Figure 7B).

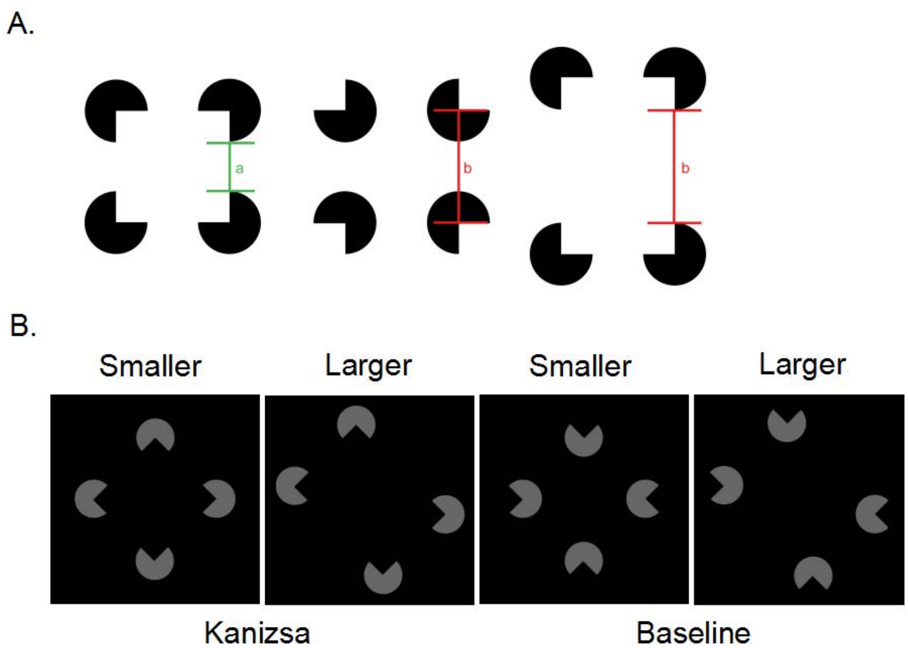



**Figure 7.** (A) Variations in spatial distance across the edges of the (smaller) Kanizsa (left panel, a) and (smaller) Baseline (middle panel, b) configurations. In the larger Kanizsa configuration (right panel), the edge length is comparable to the smaller Baseline configuration. (B) Example stimuli in Experiment 4. The smaller Kanizsa and Baseline configurations were the same as in Experiment 1.

### *Results*

Figure 8 presents the psychometric curves for the different conditions and the corresponding mean discrimination thresholds in Experiment 4 (upper and lower panels, respectively). A repeated-measures ANOVA with the factors configuration (Kanizsa, Baseline) and size (smaller, larger) on the discrimination thresholds revealed a significant main effect of configuration, $F(1, 11) = 73.54$, $p < .0001$, $\eta_p^2 = .87$, 90% CI [.65, .92], $BF_{10} = 1.16e+7$, with lower thresholds for Kanizsa ($M = 9.07$) than for Baseline configurations ($M = 20.08$). In addition, the main effect of size was significant, $F(1, 11) = 5.77$, $p = .035$, $\eta_p^2 = .34$, 90% CI [.01, .58], $BF_{10} = 0.54$: thresholds were lower for the smaller ($M = 13.20$) than for larger configurations ($M = 15.95$) – though with the $BF_{10}$ value providing no conclusive support for the alternative hypothesis. There was no interaction effect, $F(1, 11) = .18$, $p = .68$, $\eta_p^2 = .02$, 90% CI [0, .23], $BF_{10} = 0.37$. Theoretically of most importance, when equating the spatial distance between the edges of a configuration, there was still a significant difference between the smaller Baseline and the larger Kanizsa configuration, $t(11) = 4.78$, $p = .001$, $d_z = 1.38$, 95% CI [.56, 2.17], $BF_{10} = 64.75$: the threshold was lower for the larger Kanizsa ($M = 10.75$) than for the smaller Baseline configuration ($M = 19.01$).

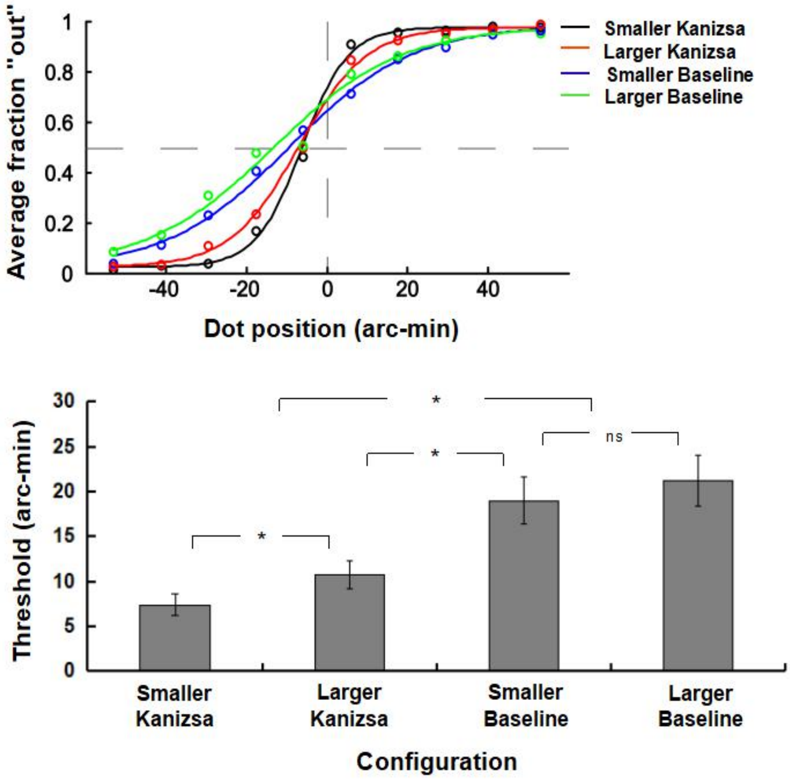



**Figure 8.** Upper panel: Psychometric curves in the dot-localization task, across observer means, in Experiment 4. The fraction of ‘out’ responses is plotted against dot position, for the smaller Kanizsa, larger Kanizsa, smaller Baseline, and larger Baseline conditions. Lower panel: Mean

discrimination thresholds in the smaller Kanizsa, larger Kanizsa, smaller Baseline, and larger Baseline conditions in Experiment 4. Error bars denote 95% within-subject confidence intervals. *$p < .05$, Bonferroni corrected.

### *Discussion*

Experiment 4 replicated the results of Experiment 1, in revealing a lower threshold for the larger Kanizsa configuration than for the Baseline even when controlling for the distance between the pacman inducers on the side on which the target dot appeared. This result indicates that the decreased discrimination threshold for the Kanizsa figure in Experiments 1 to 3 was not caused by variations in spatial distance between neighboring inducers in the various configurations. Rather, dot-localization sensitivity appears to be distinctly influenced by the completion of an illusory figure.

Moreover, Experiment 4 showed that sensitivity is reduced for the larger as compared to the smaller configurations, with this difference in size showing a particularly strong variation for the comparison between large and small Kanizsa figures ($t(11) = 4.94$, $p < .0001$, $d_z = 1.43$, 95% CI [.59, 2.23], $BF_{10} = 80.45$). This result suggests that the support ratio (i.e., the relation between the inducer disks and the illusory contour) determines the strength of the illusory figure and, as a result, perceptual sensitivity. This outcome is consistent with previous findings, which suggest that, although perceptual interpolation of subjective contours appears to be instantaneous and effortless, interpolation is constrained by spatial factors such as inducer size, inducer spacing, and overall size of the display. Larger inducers and smaller spacing between inducers have previously been shown to increase the subjective clarity of the interpolated contours (Watanabe & Oyama, 1988; Shipley & Kellman, 1992), suggesting that the perception of illusory contours is strongly tied to the support ratio (e.g., Banton & Levi, 1992; Kojo, Liinasuo, & Rovamo, 1993).

## Experiment 5

Experiment 4 ruled out the possibility that the advantage for the Kanizsa figure is due to the shorter spatial distances between the edges of the pacmen inducers. However, an alternative explanation for our findings could be that the decreased sensitivity in the Baseline (relative to the Kanizsa) configuration is owing to the edge interruption by the inducer surface, which increases the difficulty of computing a boundary. That is, the pacman inducer with outward-oriented indent would impede the formation of a connecting line between the inducer edges in the Baseline, but not in the Kanizsa configuration, thus impeding the accuracy with which the inside-outside judgment can be made. To exclude this potential confound, in Experiment 5, we eliminated the visual interruption by using variants of inducer elements that simply consisted of collinearly arranged L-shaped line junctions (see examples in Figure 9). In addition, we controlled for spatial distance between the edges of the inducers in the different configurations (comparable to the procedure adopted in Experiment 4). Processing of object configurations is usually found to be equally efficient for shapes composed of circular inducers and line segments (e.g., in visual search; see Conci et al., 2007a; 2007b). We therefore expected that dot-localization performance would be modulated by the closure of the presented configurations (i.e., revealing a benefit for the Kanizsa configurations relative to the Baseline) regardless of the presence or absence of a visual interruption caused by the inducers (pacmen vs. line junctions).

***Method***

Experiment 5 was comparable to Experiment 4, with the following differences: 12 right-handed paid volunteers (6 men; mean age: 24.25 ± 2.56 years; normal or corrected-to-normal vision) participated in the experiment. There were again four possible stimulus configurations: First, the Kanizsa and Baseline configurations were presented with pacman inducers, similar to those in Experiment 4. Second, two additional configurations were presented that consisted of four L-shaped corner junctions, with the length of each line (1.1°; line thickness: 6 arc-min) being identical to the radius of the pacman inducers (see example stimuli with line inducers in Figure 9). The corner junctions were arranged in a diamond-like form, and either presented a closed shape (Kanizsa) or a corresponding open, cross-shaped (Baseline) configuration. The pacman and line inducers in the Baseline configurations were placed at the same distance as in the Kanizsa configurations (on the side where the dot probe appeared, see Figure 9) – resulting in rectangular baseline arrangements, which allowed performance to be assessed across the various configurations independently of variations of the task-critical boundary (see above, Experiment 4). All other details of the Kanizsa and Baseline configurations with line inducers were identical to the corresponding configurations with pacman inducers.

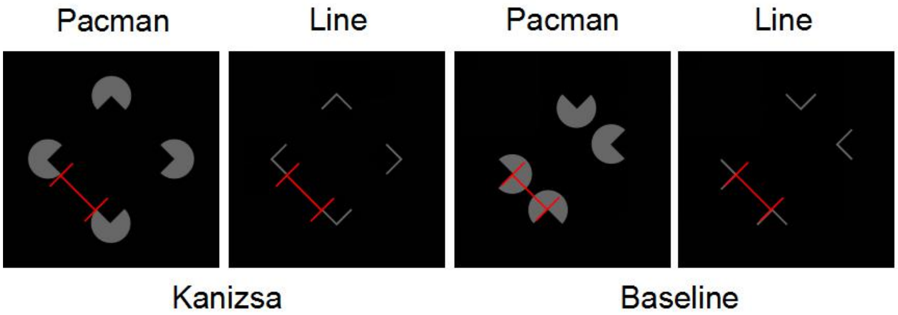



**Figure 9.** Example stimuli in Experiment 5, with variations of the inducer type in Kanizsa and Baseline configurations. In the Baseline configurations with pacman and line inducers, the edge length on the side where the dot appears is comparable to that in the respective Kanizsa configurations (see red lines; the line did not appear in the actual experiment). The Kanizsa figure was the same as in Experiment 1.

### *Results*

The psychometric curves and the corresponding mean discrimination thresholds for the different conditions are presented in Figure 10 (upper and lower panels, respectively). A repeated-measures ANOVA with the factors configuration (Kanizsa, Baseline) and inducer type (pacman, line) on the discrimination thresholds revealed a significant main effect of configuration, $F(1, 11) = 37.11$, $p < .0001$, $\eta_p^2 = .77$, 90% CI [.46, .85], $BF_{10} = 4.28e+4$, again with lower thresholds for Kanizsa ($M = 6.24$) than for Baseline configurations ($M = 12.11$). In addition, the configuration × inducer type interaction was significant, $F(1, 11) = 10.58$, $p = .008$, $\eta_p^2 = .49$, 90% CI [.1, .67], $BF_{10} = 6.12$, due to there being a significant difference between the pacman and line inducers for the Baseline configuration, $t(11) = 2.49$, $p = .03$, $d_z = .72$, 95% CI [.07, 1.35], $BF_{10} = 2.47$, but no significant difference for the Kanizsa configuration, $t(11) = 1.59$, $p = .14$, $d_z = .46$, 95% CI [-.15, 1.05], $BF_{10} = .77$. Note, though, that a significant reduction of the threshold for Kanizsa relative to Baseline configurations was found for both types of inducer: pacman inducers: $t(11) = 6.42$, $p < .0001$, $d_z = 1.85$, 95% CI [.89, 2.79], $BF_{10} = 530.97$; and line inducers: $t(11) = 2.95$, $p = .01$, $d_z = .85$, 95% CI [.17, 1.51], $BF_{10} = 4.75$]. Finally, there was no effect of inducer type, $F(1, 11) = .62$, $p = .45$, $\eta_p^2 = .05$, 90% CI [.00, .30], $BF_{10} = .33$.

As can be seen from Figure 10 (upper panel), the PSE appears to be shifted from the objective contour location, in particular for the Kanizsa configurations. We therefore tested the deviation from the objective location with a series of one-sample t-tests (2-tailed), as in Experiment 1. Both the PSE of the Kanizsa configurations with pacman and line inducers showed a significant deviation from the objective contour location, but interestingly in opposite directions: as in Experiment 1, the pacman version of the Kanizsa configuration exhibited a deviation towards inside locations ($M = -3.74$), $t(11) = -3.01$, $p = .012$, $d_z = -.87$, 95% CI [-1.52, -.19], $BF_{10} = 5.15$; by contrast, the line-inducer version of the Kanizsa configuration showed a deviation towards outside locations ($M = 5.43$), $t(11) = 2.38$, $p = .036$, $d_z = .69$, 95% CI [.04, 1.31], $BF_{10} = 2.12$. [All Baseline conditions, $ts(11) < 1.9$, $ps > .08$, all $d_z < .55$, all $BF_{10} < 1.1$.]

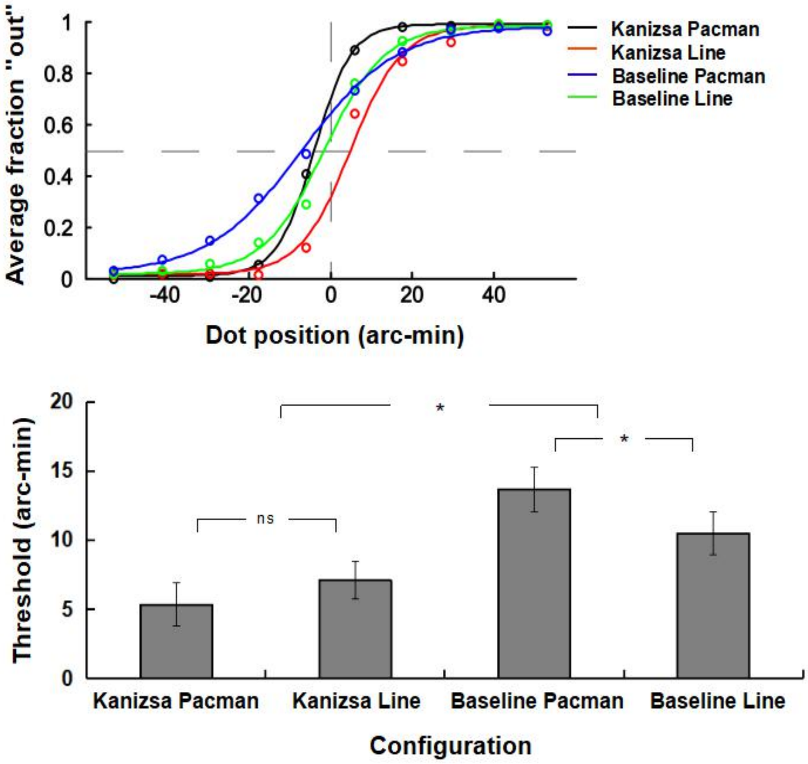



**Figure 10.** Upper panel: Psychometric curves in the dot-localization task, across observer means, in Experiment 5. The fraction of ‘out’ responses is plotted against dot position, for the Kanizsa and Baseline configurations, separately for pacman and line inducers. Lower panel: Mean discrimination thresholds in the Kanizsa and Baseline configurations with pacman/line inducers in Experiment 5. Error bars denote 95% within-subject confidence intervals. *$p < .05$, Bonferroni corrected.

### *Discussion*

Experiment 5 revealed a reduced dot-localization sensitivity for Baseline than for Kanizsa configurations, which was largely independent of inducer type. This shows that the observed performance difference can be attributed to the completion of an illusory figure, which enhances perceptual sensitivity irrespective of any visual edge interruption produced by the pacman inducer surface (in the Baseline condition). However, despite a clear effect of grouping upon performance, the interruption nevertheless modulated the efficiency of dot localization in the Baseline configurations. In particular, thresholds were reduced in Baseline configurations with (non-interrupted) line inducers as compared to (interrupted) pacman inducers – showing that without an emergent figure, the computation of a task-relevant object boundary depends on the efficiency with which inducers can be integrated to form a connecting line. Of note, this finding is essentially the same as the reduction of sensitivity in Experiment 2 relative to Experiment 1, where the addition of circular rings to the inducers (in Experiment 2) resulted in an overall performance decrease due to the interruption of the connection between neighboring pacman inducers.

In addition, Experiment 5 revealed another interesting result, namely: the PSE for Kanizsa configurations with pacman and line-inducers deviated from the objective contour location in opposing directions. In particular, participants tended to perceive the boundary of the Kanizsa configuration with pacman inducers as being curved towards the inside (as in Experiment 1), and with line inducers as being curved towards the outside. Comparable findings were reported in previous studies with pacman (Guttman & Kellman, 2004; Gintner et al., 2016) and line (Gegenfurtner, Brown, & Rieger, 1997; Conci et al., 2007b) inducers. With the line inducers, this 'outside' bias might arise because observers perceive an illusory square that appears to be completed in front of the L-inducer, diamond-shaped grouping.

## General Discussion

In the current study, we probed the sensitivity of illusory figure perception by means of a dot-localization task, and established separable influences of contour- and surface-related processing by gradually manipulating various aspects of grouping in the stimulus configurations. Sensitivity was estimated from the discrimination threshold of the psychometric functions of dot-localization performance: the lower the discrimination threshold (i.e., the steeper the slope), the higher the sensitivity. Experiment 1 showed that sensitivity was modulated by both the amount of surface and contour information present in a given configuration, with the highest sensitivity for (complete) Kanizsa figures, followed by Shape and Contour configurations, and the lowest sensitivity for the Baseline configuration. This pattern indicates that both surface filling-in and contour interpolation contribute to the formation of the illusory figure. In Experiment 2, the same experimental logic was applied to occluded object configurations. For the amodally completed stimuli, the sensitivity was overall reduced (i.e., in Kanizsa, Shape, and Contour stimuli). In addition, while the difference between Contour and Baseline stimuli disappeared, Kanizsa and Shape configurations still afforded higher sensitivity than Contour and Baseline configurations – suggesting that the formation of an illusory surface continued to facilitate performance even when contour interpolation processes were not available (due to object occlusion). Next, in Experiment 3, separable processing of contour and surface information was further investigated by presenting modal completion configurations with smoothed inducers, which group to form a coherent surface region but without concurrent illusory contours. The results from these "salient-region" stimuli again showed an increased perceptual sensitivity relative to the Baseline configurations. Thus, together, the results of Experiments 2 and 3 consistently show that contour and surface processing can be dissociated to some extent in the completion of an illusory figure, that is, they provide separable influences on performance. Finally, Experiments 4 and 5 were performed as control experiments to confirm that the performance benefit for Kanizsa figures was due to the completion of an illusory figure, rather than being attributable to subtle variations in distance between the pacman elements in the configurations presented (Experiment 4), or due to visual (edge) interruption which interferes with the computation of a boundary in the Baseline configuration (Experiment 5).

Taken together, our results support the view that the completion of illusory contours and surfaces provide essential contributions to the formation of illusory Kanizsa figures, as both contribute to dot-localization performance (see Experiments 1–3). This supports common explanations of the underlying mechanisms of modal completion (see Pessoa et al., 1998, for a review), and is consistent with previous observations that both processes of surface and contour grouping are available pre-attentively (Conci et al., 2009; see also Mattingley, Davis, & Driver, 1997). At the same time, however, the results are, to some extent, inconsistent with findings from visual search, which indicated that only the surface but not the surrounding contours determine the efficiency of detecting Kanizsa figure targets among distractors (Conci et al., 2007a). This difference in results is likely attributable to differential task requirements, as the role of contour interpolation might be underestimated in a visual search task where attention is to be focused on a relatively broad representation of the Kanizsa target shape (see also Stanley & Rubin, 2003). In this view, the allocation of attention appears to be determined by the specifics of a given task: a relatively broad estimation of a salient region might suffice to detect an illusory square in visual search, whereas the dot-localization task engenders more precise discrimination processes that require the engagement of both contour and surface completion to render a more precise shape representation.

In general, mechanisms of figure-ground segregation are thought to be involved in integrating inducer information so as to represent an illusory surface as lying in front of the pacman inducer disks (Kogo et al., 2010; Kogo & Wagemans, 2013). Note that we found that surface construction processes yield a performance benefit even when illusory contours are not perceived due to occlusion (Experiment 2), or as a result of smoothed pacmen inducers (Experiment 3). Although it is not possible to perceive explicit, definitive contours with these variants of the illusory objects, observers nevertheless appeared to perceive the continuation of the surface behind the pacmen, or a salient region that was formed in the absence of sharp boundaries, and, as a result, detected the illusory shape, leading to an increase of their perceptual sensitivity (see also Van Lier, 1999).

To explain how Kanizsa figures are completed, it has been proposed that processing of the illusory figure is accomplished by a feedforward, serial mechanism (Grosof, Shapley, & Hawken, 1993; Ffytche & Zeki, 1996), during the operation of which surface filling-in is achieved only after the interpolation of the respective illusory contours. In this view, the boundaries of an object are computed first and the surface is generated only afterwards. However, the present results provide strong evidence that illusory contours and the corresponding surfaces are computed by separate mechanisms that are not necessarily dependent on each other (see also Grossberg & Mingolla, 1985; Dresp & Bonnet, 1991; Dresp, Lorenceau, & Bonnet, 1990; Rogers-Ramachandran & Ramachandran, 1998). In fact, illusory surfaces can be generated without an exact specification of the illusory contours that demarcate the object boundaries (Experiments 2 and 3; see also Stanley & Rubin, 2003). This pattern, of separable processing of contours and surfaces, is difficult to explain by a serial, feedforward process. Arguably, a better explanation is provided by recurrent models of completion, on which completion of illusory figures results from a series of feedforward and feedback loops, with processing operating in parallel at various levels in the visual hierarchy (Lamme & Roelfsema, 2000; Roelfsma, Lamme, Spekreijse, & Bosch, 2002; Kogo et al., 2010; Kogo & Wagemans, 2013). On such a recurrent-network account, different object components may be specified with relative independence of each other. For instance, parallel, feedforward processing may initially extract contours and surfaces independently of each other via separate mechanisms. The combination of their outputs is then accomplished by a recurrent feedback process that combines the estimated surface with the associated contours to form a coherent whole.

In line with this account, Stanley and Rubin (2003) reported fMRI evidence suggesting that the visual system first detects the “salient regions” of an object at higher cortical levels (e.g., in the LOC; Seghier & Vuilleumier, 2006), and this crude region estimation is then complemented by contour-sensitive processes in lower cortical regions (V1/V2 regions) through a top-down feedback loop that, in turn, refines the perception of the surface and determines its precise edges. Moreover, Shpaner, Molholm, Forde, and Foxe (2013) reported evidence to suggest that the flow of information via feedforward and feedback connections across various levels in the visual hierarchy facilitates the perception of the whole illusory figure. In general agreement with these accounts, the current findings show that completion of illusory contours is supported by complementary processes of surface filling-in, yielding higher sensitivity for Kanizsa and Shape compared to Contour configurations (see Experiment 1). This might be the result of a refined object representation that first extracts the respective surface and contour information, with subsequent, recurrent feedback iterations combining these sources of information to represent the whole illusory figure.

## Conclusions

Object completion – as exemplified in the Kanizsa figure – is a fundamental operation of human vision and observed in many instances, with the representation of a coherent whole determining all subsequent higher-order cognitive and emotional processing (see, e.g., Erle, Reber, & Topolinski, 2017). Thus, identification of the mechanisms underlying object completion (in Kanizsa figures) is essential for a complete understanding of human vision. The current study established an approach for effectively investigating these mechanisms by examining illusory figure sensitivity using a dot-localization task while comparing and contrasting the relative impact of the available contour and surface information. Collectively, the results obtained provide further support for a multi-stage model of object processing. Illusory contour and surface completions are both closely related to fundamental mechanisms of the visual system by which illusory figures are grouped, interacting through a series of feedforward and feedback loops.

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## 2.2 Study 2: Kanizsa-figure object completion gates selection in the attentional blink

Contributions:

The author of this dissertation designed and programmed the experiment, collected and analyzed data, created plots, interpreted the results and wrote the manuscript.

Qiyang Nie helped with programming the experiment and he commented on the manuscript.

Hermann Müller contributed to the interpretation of the results. He commented on and helped revising the manuscript.

Markus Conci conceived and supervised the project, participated in designing the experiments and interpreted the results. He commented on and helped revising the manuscript.

# Kanizsa-figure object completion gates selection in the attentional blink

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## Abstract

Previous work has demonstrated that perceptual grouping modulates the selectivity of attention across space. By contrast, how grouping influences the allocation of attention over time is much less clear. The current study investigated this issue, using an attentional blink (AB) paradigm to test how grouping influences the initial selection and the subsequent short-term memory consolidation of a target. On a given trial, two red Kanizsa-type targets (T1, T2) with varying grouping strength were embedded in a rapid serial visual presentation stream of irrelevant distractors. Our results showed the typical AB finding: impaired identification of T2 when presented close in time following T1. Moreover, the AB was modulated by the T2 grouping – independently of the T1 structure – with stronger grouping leading to a decreased AB and overall higher performance. Conversely, a reversed pattern, namely an increased AB with increasing grouping strength was observed when the Kanizsa figure was not task relevant. Together, these findings suggest that the grouping benefit emerges at early perceptual stages, automatically drawing attentional resources, thereby leading to either sustained benefits or transient costs – depending on the task-relevance of the grouped object. This indicates that grouping modulates processing of objects in time.

## Introduction

The organization of fragments and parts into coherent wholes is a central problem for visual perception. For instance, Kanizsa subjective figures (Figure 1A, complete; Kanizsa, 1955) give rise to a well-known visual illusion: the percept of an object with sharp contours and a brighter-than-background surface even though there is no actual luminance discontinuity in the physical stimulus. Kanizsa figures thus illustrate that the visual system can bind together separate parts (such as the "pacman" inducers in a Kanizsa figure) to produce a vivid impression of an integrated and coherent object. In this particular case, the association of distinct elements into a coherent whole has been shown to be governed by a set of Gestalt principles, such as collinearity and closure (Koffka, 1935; Wertheimer, 1923; see Brooks, 2015, for a recent review).

Visual search studies have consistently shown that component parts may be grouped prior to the engagement of attention (e.g., Moore & Egeth, 1997; Rensink & Enns, 1995). The critical measure in a visual search task is usually the time required to detect a particular target among a variable number of distractors. If the target is distinguished by a property that can be efficiently coded in parallel across the visual field, then it should "pop out", that is: search performance should not be affected by the number of distractors in the display. For instance, the search time for a target Kanizsa figure (Figure 1A, complete) is little affected by the number of distractor configurations (Figure 1A, ungrouped) that are composed of the same pacmen but do not induce an illusory figure (Conci, Müller, & Elliott, 2007a, 2009; Davis & Driver, 1994; Senkowski, Röttger, Grimm, Foxe, & Herrmann, 2005). Moreover, search for a Kanizsa target figure is far more efficient than search for a comparable "ungrouped" target configuration that does not render an illusory object, even though in both variants of the search task, the same distractor configurations were used, which were equally similar to both types of target (Conci et al., 2007a; Conci, Töllner, Leszczynski, & Müller, 2011). Together, these findings suggest that efficient search for Kanizsa figures is guided by grouping principles (i.e., collinearity and closure) that operate at early stages of visual processing, that is, prior to the engagement of attention (Conci, Müller, & Elliott, 2007b; Nie, Maurer, Müller, & Conci, 2016).

Integrated object configurations such as the Kanizsa figure have also been shown to automatically capture spatial attention. For example, search for a target disk in an array of randomly oriented (pacmen) distractor disks is substantially slowed when an illusory square is present (vs. absent) in the display (Rauschenberger & Yantis, 2001). Other experiments used search arrays containing a Kanizsa figure as a non-informative spatial 'cue' for a target that required a speeded choice reaction. Faster responses were obtained for a target presented inside, as compared to outside, the Kanizsa figure cue (Senkowski et al., 2005). Findings such as these suggest that a single integrated, illusory figure provides salient information, summoning an attentional orienting response to the region delineated by the grouped object (see also Marini & Marzi, 2016).

Whereas much of the previous work has elucidated how perceptual grouping modulates the allocation of selective attention across space, we know, as yet, little about how attentional selection is influenced by perceptual grouping over time. Temporal modulation of attention is frequently studied using the "attentional blink" (AB) paradigm, in which observers are asked to detect two targets presented successively within a rapid serial visual presentation (RSVP) stream of nontarget items (e.g., letters, words, or symbols) at a single location. While detection of the first target (T1) usually reveals a relatively high level of performance, detection of the second target (T2) is impaired if the temporal gap between the two targets is less than ~500 ms, while improving again at longer lags (Broadbent & Broadbent, 1987; Chun & Potter, 1995; Raymond, Shapiro, & Arnell, 1992). This transient drop in performance, which is referred to as the AB, has been assumed to reflect the temporal profile of attention.

The dual-target RSVP task can be thought of as a time-based analog of a visual search task (Vogel, Luck, & Shapiro, 1998). However, their underlying attentional mechanisms are not necessarily identical. Whereas processes of spatial attentional selection (e.g., in visual search) start to operate at an early, pre-attentive stage of processing, before stimulus identification is complete (see Luck, 1998, for review), the AB potentially reflects a post-perceptual attentional mechanism that marks the transition between perceptual stimulus analysis and the subsequent storage of selected items in a capacity-limited working memory buffer (Vogel et al., 1998). For instance, a prominent two-stage model to account for the AB (Chun & Potter, 1995) assumes that stage 1 involves perceptual coding of all stimuli in the RSVP stream; however, due to interference arising from the sequential mode of stimulus presentation, the encoded items decay rapidly over time, because each item is displaced by the subsequently presented item in the RSVP stream (see also Woodman & Luck, 2003; Moore & Lleras, 2005). To prevent or minimize interference, attentional resources are required to consolidate the “fragile” stimulus representations from stage 1 into a more stable and long-lasting format during stage 2 processing, that is, the consolidation of a selected number of items into working memory (see also Jolicœur & Dell’Acqua, 1998; Potter, Staub, & O’Connor, 2002; Shapiro, Raymond, & Arnell, 1997). Within this framework, an AB is thought to result from a failure of T2 to achieve stage 2 processing, because the capacity-limited consolidation mechanism is preoccupied with the processing of the preceding T1 stimulus (Vogel et al., 1998; Shapiro, Raymond, & Arnell, 1994).

Here, we investigated whether and how grouping structure in targets influences the profile of temporal attention. Although time-based selection operates only after initial visual processing, perceptual factors may nevertheless influence the AB (see e.g., Chen, Müller, & Conci, 2016, for effects of grouping on working memory). Previous studies, in fact, have shown that the AB is reduced when the perceptual salience of T2 is increased, for example, by increasing its featural and spatial dissimilarity to the distractors (Raymond, Shapiro, & Arnell, 1995) or by presenting highly arousing words (Anderson, 2005; Keil & Ihssen, 2004; Keil, Ihssen, & Heim, 2006) or familiar and emotional faces (Jackson & Raymond, 2006; Stein, Zwickel, Ritter, Kitzmantel, & Schneider, 2009) as T2s. To explain these findings, it has been suggested that salient stimuli are less susceptible to the AB because they generate a high level of (perceptual) activity that takes more time to decay, thus bridging the temporal gap during which resources are unavailable for encoding items into working memory (e.g., Anderson, 2005). On this background, we hypothesized that grouping in Kanizsa figures would lead to the formation of a salient object (Davis & Driver, 1994; Senkowski, et al., 2005; Conci, et al., 2007a; Rauschenberger & Yantis, 2001) that, in turn, would be relatively resistant against decay and more efficiently consolidated in spite of the limited capacity available, thus attenuating the AB.

To test this prediction, the present study investigated how perceptual grouping influences the AB using Kanizsa figures and comparable “ungrouped” control figures as targets. For instance, Experiment 1 implemented an RSVP stream of object configurations presenting circular placeholders in various colors. Observers were required to identify two uniquely colored (namely, red) target configurations. As illustrated in Figure 1A, the strength of grouping in the T2 configuration was gradually varied, ranging from a complete grouping (a Kanizsa star shape; Figure 1A left) through a partially grouped (three of six inducers form a Kanizsa triangle; Figure 1A middle) to an "ungrouped" configuration (no closure, all inducers point outwards; Figure 1A right) – thus systematically varying closure in the Kanizsa-type configurations. Note that the various pacman configurations changed in terms of the strength of grouping they engendered, however without changing the low-level properties of the image. The crucial question concerned whether the accuracy of identifying the T2 target configuration would vary as a function of its grouping strength. That is, by systematically varying the T1–T2 lag, we examined whether the grouping structure of T2 would modulate the AB effect.

## Experiment 1

Experiment 1 was performed to investigate how T2 grouping strength influences the AB. On a given trial, distractor arrangements of six colored disks (all disks of the same color, but not red) were presented in rapid succession. Within this stream, two arrangements were presented in red and these were defined as the target configurations. Targets were presented with small segments removed from each disk, which, by appropriately rotating the cutout segments, would create the impression of a Kanizsa figure. T1 was always defined as a grouping (of cutout disks) that would not lead to the emergence of an illusory figure, and T2 was either a complete (Kanizsa star shape), or a partially grouped (Kanizsa triangle shape), or an ungrouped configuration (see Figure 1A). This manipulation permitted us to examine whether a systematic variation of the grouping strength in T2 would influence the AB.

### *Method*

***Participants.*** Fifteen right-handed volunteers (7 male; mean age: 24.67 ± 2.26 years) with normal or corrected-to-normal visual acuity and (self-reported) normal color vision participated in the experiment for payment of €8.00 per hour. The experimental procedure was approved by the ethics committee of the Department of Psychology, Ludwig-Maximilians-Universität München, and all participants provided written informed consent. Sample size was determined on the basis of previous, comparable studies (e.g., Stein et al., 2009), aiming for 85% power to detect a medium effect size (within-participants; f=0.25; Cohen, 1988) given an alpha level of .05.

***Apparatus.*** The experiment was conducted with an IBM-PC compatible computer using Matlab routines and Psychophysics Toolbox extensions (Brainard, 1997; Pelli, 1997). Stimuli were presented in different colors against a gray (RGB: 125, 125, 125; 51.7 cd/m$^2$) background in the center of a 17-inch computer monitor (1024×768 pixel screen resolution, 85-Hz refresh rate). The experiment was conducted in a sound-attenuated room that was dimly lit with indirect incandescent lighting.

***Stimuli.*** Each trial consisted of a series of configurations that were presented in different colors. Each configuration was composed of six colored disks (each subtending a viewing angle of 3.3°) arranged around a circle (with a radius of 5.2°, at a viewing distance of 50 cm). Distractor configurations were composed of six complete disks presented in four different colors – green (RGB: 75, 184, 72), purple (RGB: 137, 41, 143), yellow (RGB: 243, 236, 27), or blue (RGB: 22, 148, 210) – which were selected at random, with the only restriction that two consecutive configurations never shared the same color. Two target configurations composed of six pacmen inducers (i.e., disks with quarter segments removed) were presented in red color (RGB: 236, 30, 39). The first target (T1) was presented with all pacmen inducers oriented either up- or downwards (see Figure 1A). The second target (T2) either presented a complete Kanizsa figure (a star shape), a partially grouped Kanizsa triangle (with the triangle presented in up- or downward orientation), or an ungrouped object (with all pacmen inducers rotated outwards by 180°), thus gradually varying the grouping strength of T2 by means of a decrease in object closure (see Figure 1A).

***Procedure and Design.*** As depicted in Figure 1B, each trial started with the presentation of a central fixation cross for 500 ms at the screen center, followed by the RVSP stream. Each configuration was presented for 100 ms, followed by a short blank interval of 20 ms, resulting in a stimulus onset asynchrony (SOA) of 120 ms. On a given trial, the first target (T1) was randomly allocated to one of three temporal serial positions, from 2 to 4, within the stream of 10 configurations. The second target (T2) was presented at one of four different temporal lags (120, 240, 360, or 600 ms, corresponding to serial lag positions 1, 2, 3, or 5) subsequent to T1. RSVP stream distractors continued to be presented during the lag and after T2. Following the presentation of the RSVP stream, a blank screen appeared until a response was issued.

Participants were instructed to detect the two red targets. With regard to T1, participants were asked to identify the pointing direction of the T1 pacmen with a right (upward) or left (downward) mouse button press, using (the index or the middle finger of) the right hand. With regard to T2, the task was to report the number of triangles that were presented within a given target configuration, that is: “0” for the ungrouped object, “1” for the partially grouped object, and “2” for the complete object grouping. Participants responded with a left-hand button press via keyboard, pressing the left-, down-, or rightward arrow key for “0”, “1”, or “2” triangles, respectively. Feedback was provided at the end of each trial by displaying a white and/or a red “—” sign for 500 ms on the screen if an error had occurred for the first and/or the second target, respectively. Trials were separated from one another by an interval of 1000 ms. Observers were instructed to respond as accurately as possible, with particular emphasis on T1 accuracy in order to maximize the number of trials available for the analysis of T2 accuracy. Every participant completed 20 blocks of 24 trials each, following one practice block of 24 trials (giving a total of 504 trials). After each block, participants took a short break; they then proceeded to the next block by pressing the ‘space’ bar following a message on the screen.

In summary, the experiment systematically varied two factors: T2-target type (complete, partially grouped, and ungrouped object), and T1–T2 lag (Lag 1, 2, 3, or 5), with all possible factorial combinations presented in random order.

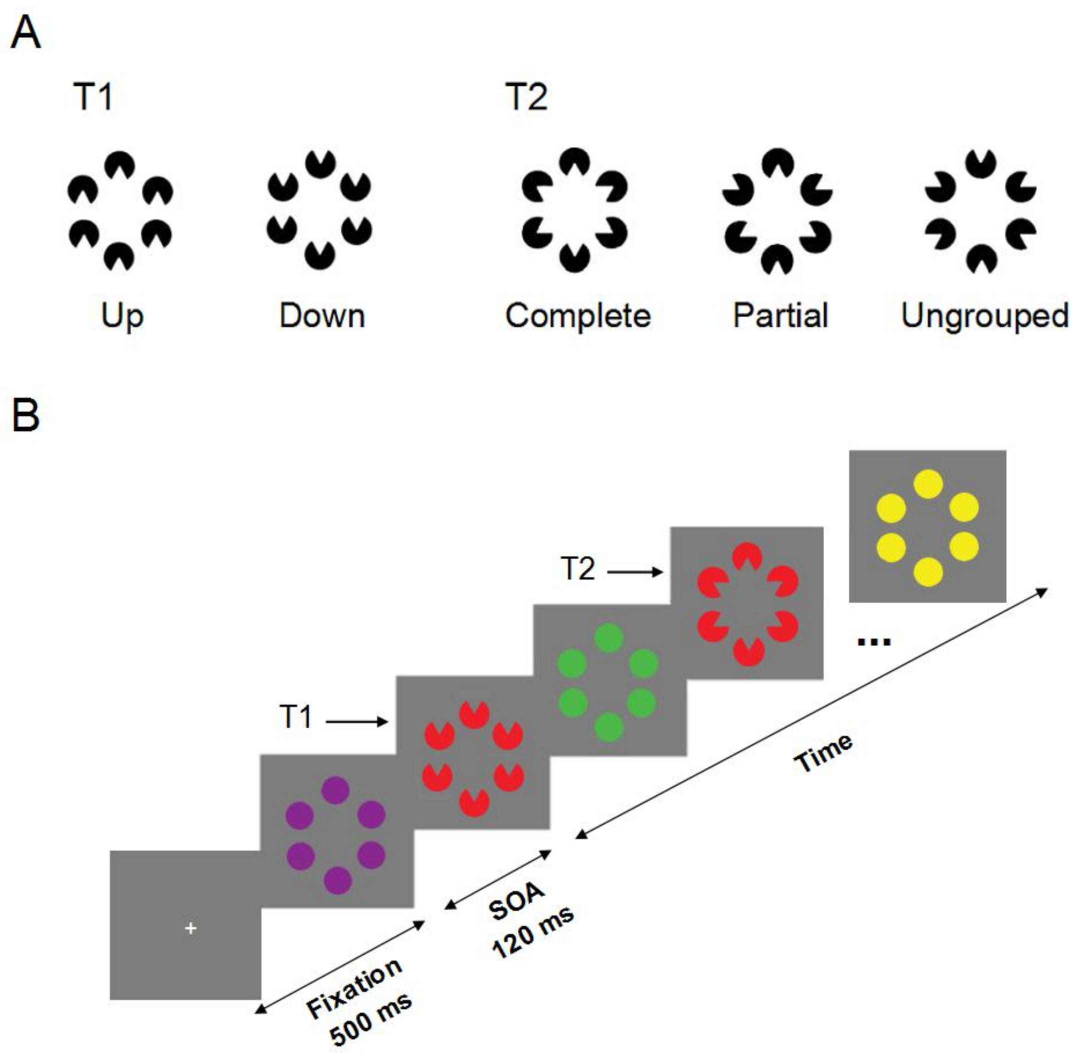


**Figure 1.** Stimuli and display sequence in Experiment 1. (A) Illustration of experimental stimuli for T1 (all pacman inducers oriented either up- or downwards) and T2 (left: complete; middle: partially grouped; right: ungrouped). (B) Schematic example of the RSVP sequence. Each trial presented a sequence of 10 displays, which consisted of either six complete distractor disks (non-red items) or the T1 and T2 target arrangements (red items).

### *Results*

***T2 accuracy.*** Estimates of T2 accuracy were based solely on trials on which T1 had been identified correctly (as it is hard to determine the effect on the processing of T2 when the cause of the erroneous response to T1 is not known). Figure 2 presents T2 accuracy as a function of lag, separately for the different target conditions. A two-way repeated-measures analysis of variance (ANOVA) of correct T2 responses, with the factors T2-target type (complete, partially grouped, ungrouped) and lag (1, 2, 3, 5), revealed both main effects to be significant: T2-target type, $F(2, 28) = 6.67$, $p = .004$,

$\eta_p^2 = .32$, 90% confidence interval, or CI [.07, .48]; lag, $F(3, 42) = 24.12$, $p < .0001$, $\eta_p^2 = .63$, 90% CI [.45, .71]. For the post-hoc comparisons, given that such repeated testing increases the chance of a significant effect, a Bonferroni correction was applied (Neter & Wasserman, 1974). There was a graded effect of target type, with the highest accuracy for complete configurations (86%), followed by partially grouped (81%) and ungrouped (74%) configurations (complete vs. ungrouped: $p = .001$; partially grouped vs. ungrouped: $p = .39$; partially grouped vs. complete: $p = .31$). In addition, there was a monotonic increase of performance from lag 1 onwards (76%, 77%, 83%, and 87% for lags 1, 2, 3, and 5, respectively; *p*s < .029). Furthermore, the T2-target type × lag interaction was significant, $F(6, 84) = 2.68$, $p = .02$, $\eta_p^2 = .16$, 90% CI [.01, .23]. To decompose this interaction, the AB amplitude was computed (see also Anderson, 2005), which is defined as the maximum difference in performance across lags, that is, contrasting the (early) lag(s) with the lowest accuracy with (later) lag(s) that resulted in the highest level of accuracy (e.g., in Experiment 1, the largest difference was revealed between lag 1 and lag 5). Comparisons of the AB amplitude across target type conditions revealed difference in amplitude to be largest for ungrouped (15%), intermediate for partially grouped (11%), and smallest for complete configurations (6%), $F(2, 28) = 3.47$, $p = .045$, $\eta_p^2 = .20$, 90% CI [.00, .36].

***T1 accuracy.*** The mean percentage of correct responses for T1 was 90%. A two-way repeated measures ANOVA with the factors T2-target type (complete, partially grouped, ungrouped) and lag (1, 2, 3, 5) revealed only a lag effect: $F(3, 42) = 35.49$, $p < .0001$, $\eta_p^2 = .72$, 90% CI [.56, .78]. T1 performance exhibited a drop at lag 1: 80%, 92%, 93%, and 94% for lags 1, 2, 3 and 5, respectively (*p*s < .0001); that is, the short lag between T1 and T2 (also) impacted the accuracy of reporting T1. Importantly, however, no (main or interaction) effect involving T2-target type was revealed (*F*s < 1.5, *ps* > .25).

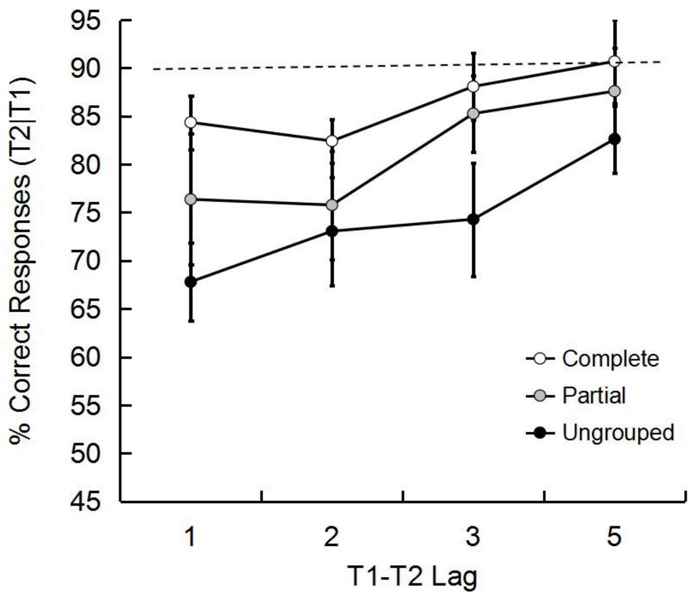


**Figure 2.** Mean percentage of correct identifications of T2 (given a correct T1 response) in Experiment 1. Correct identifications are presented as a function of the temporal lag from the onset of T1 to the onset of T2, separately for the different T2-target types (complete, partially grouped, and ungrouped configurations). The dashed horizontal line indicates the level of overall T1 accuracy. Error bars denote 95% within-subject confidence intervals.

### *Discussion*

The pattern of results in Experiment 1 clearly demonstrates that T2-targets are the less susceptible to the AB the higher their grouping strength: the AB amplitude was smallest for the complete, intermediate for partially grouped, and largest for ungrouped T2 configurations. In addition, the overall T2 accuracy also depended on the grouping strength, with higher performance for the more grouped objects. Importantly, there was no influence of the T2 grouping type on T1, that is, the enhanced accuracy for complete and partially grouped T2s cannot be explained in terms of a trade-off between T2 and T1 accuracy. Our finding that grouping was associated with a diminished AB suggests that attention was more effectively allocated to grouped stimuli. This is in line with findings from previous studies on the spatial allocation of attention, which have been taken as evidence for the preattentive coding of Kanizsa figures (e.g., Davis & Driver, 1994; Senkowski, et al., 2005; Conci, et al., 2007a; Rauschenberger & Yantis, 2001). This benefit of grouping manifested even though the complete and ungrouped objects consisted of identical physical stimulus components and were of equal object complexity (in terms of the descriptive criteria of Garner & Clement, 1963). However, there still remained a lag-dependent impairment for the grouped T2, which (although the decrement became smaller with increasing lag) would appear to be at variance with the view that the illusory shape is processed completely independently of attention (see also Joseph, Chun, & Nakayama, 1997).

Despite monotonic increases in T2 identification with longer T1–T2 lags, many studies have reported an effect of "lag-1 sparing" in which performance is relatively unimpaired if T2 is presented directly after T1 (e.g., Chun & Potter, 1995; Raymond et al., 1992). A potential explanation for this sparing effect is that the visual system tends to process the two targets together (e.g., in a batch) as long as they appear in direct temporal succession (Chun & Potter, 1995). However, it has also been shown that lag-1 sparing occurs in particular when no attentional switch (e.g., across locations, tasks, or categories) is required between targets (Visser, Bischof, & Di Lollo, 1999; see also Juola, Botella, & Palacios, 2004). Lag-1 sparing is in addition crucially dependent on the temporal separation between targets, with reliable sparing being evident predominantly with lags shorter than 100 ms (Olivers & Meeter, 2008; Potter, Staub, & O'Connor, 2002). The results from Experiment 1 failed to show spared lag-1 performance; rather, the AB was particularly pronounced at lag 1. This may have resulted from the attentional switch between two targets (from a local-object direction discrimination task to a global-shape "counting" task) and from the relatively long T1–T2 lag (120 ms; see also Conci & Müller, 2009).

**Experiment 2**

Experiment 1 showed that T2 grouping strength modulates the AB when T1 is an ungrouped configuration that requires the identification of the (individual) pacman's pointing direction. In Experiment 2, we investigated whether grouping in T1 might also influence T2 processing. This was motivated by findings that the AB may actually be increased following a salient T1 (Martens & Wyble, 2010; i.e., the converse of the reduction of the AB by a salient T2). This has been attributed to the increased salience of T1 engendering a longer dwell of attention (on the T1) and thus reducing the capacity available for the processing of T2 (Stein et al., 2009; Huang, Baddeley, & Young, 2008). In Experiment 2, we therefore increased the strength of the T1 grouping by presenting a partially grouped Kanizsa triangle in order to examine whether the selection of a grouped T1 would impede the consolidation of complete, partially grouped, and ungrouped T2 configurations.

Recall that the AB modulation by means of the T2 grouping strength in Experiment 1 was maximal at early temporal lags, but a substantial difference between configuration types nevertheless remained until later lags. For instance, the complete T2-target gave rise to a significantly higher accuracy than the ungrouped T2 across all lags (significant main effect of T2-target type), and this difference persisted even until lag 5, that is, 600 ms after the presentation of T1, $t(14)=2.56$, $p = .023$, $d = .66$, 95% CI [.09, 1.21]. A potential explanation for this sustained difference between T2 groupings might be that the temporal interval between T2 and T1 was simply not long enough, even at lag 5; that is, selection of T2 some 600 ms after T1 might still be compromised due to the attentional demands of processing the preceding T1. An alternative explanation might be that the benefit of grouping at longer lags reflects an additional advantage that arises from post-selective processing (i.e., at stage 2). In this view, how efficiently a given target configuration is consolidated into short-term memory would vary for the various types of grouping. To address this issue, in Experiment 2, the temporal lags were extended (beyond lag 5) up to lags 6 and 7. More precisely, T2 was presented at one of four different temporal lags (120, 240, 720, or 840 ms, corresponding to serial lag positions 1, 2, 6, or 7), thus covering an extended time interval subsequent to T1.

### *Method*

Experiment 2 was methodologically identical to Experiment 1, except that the T1 configuration was always a partial grouping that induced a Kanizsa triangle which pointed either up- or downwards (see Figure 3). The T1 task was roughly comparable to Experiment 1: it required observers to identify the pointing direction of the triangular T1 grouping (up- vs. downwards). With respect to T2, observers had again to determine the number of triangles (as in Experiment 1). In addition, compared to Experiment 1, the T1–T2 lags were extended. On a given trial, T1 was randomly allocated to one of three temporal serial positions, from 2 to 4, within a stream of now 12 configurations. T2 was then presented at one of four different temporal lags (120, 240, 720, or 840 ms, corresponding to serial lag positions 1, 2, 6, or 7) subsequent to T1. As in Experiment 1, RSVP stream distractors continued to be presented during the lag and after T2. Fifteen right-handed volunteers (7 males; mean age: 23.00 ± 2.83

years) with normal or corrected-to-normal visual acuity participated in the experiment for payment of € 8.00 per hour. Each participant completed 24 practice plus 480 experimental trials (divided into 20 blocks).

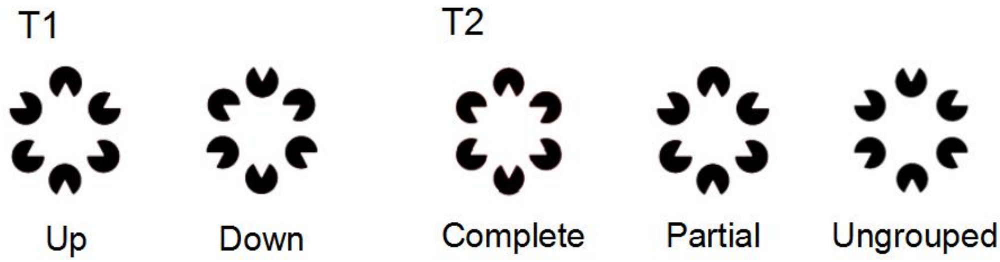


**Figure 3**. Example target configurations for T1 (up vs. downward pointing triangles) and T2 (complete, partially grouped, or ungrouped) in Experiment 2.

## *Results*

***T2 accuracy.*** Figure 4 presents the T2 accuracy (given a correct T1 response) as a function of lag, separately for the different target type conditions. A two-way repeated-measures ANOVA of correct T2 responses with the factors T2-target type (complete, partially grouped, ungrouped) and lag (1, 2, 6, 7) revealed both main effects to be significant: target type, $F(2, 28) = 14.12$, $p < .0001$, $\eta_p^2 = .50$, 90% CI [.24, .63] and lag, $F(3, 42) = 28.80$, $p < .0001$, $\eta_p^2 = .67$, 90% CI [.50, .74]. T2 accuracy was higher for complete (85%) than for partially grouped (73%; $p = .004$) and ungrouped (71%; $p < .0001$) configurations; there was no significant accuracy difference between partially grouped and ungrouped configurations ($p = 1$). Moreover, T2 accuracy increased with T1–T2 lag (67%, 69%, 84%, and 86% for lag 1, 2, 6, and 7, respectively), revealing a significant increase from lag 2 onwards ($p$s <.001), but no significant difference for the lag-1 vs. lag-2 comparison ($p = 1$). In addition, the T2 target type × lag interaction was significant, $F(6, 84) = 2.34$, $p = .039$, $\eta_p^2 = .14$, 90% CI [.00, .21], mainly due to a performance difference between the complete and ungrouped condition, $F(3, 42) = 6.88$, $p = .001$, $\eta_p^2 = .33$, 90% CI [.11, .45]: the AB amplitude (lags 1/2 vs. 7) was larger for ungrouped (22%) compared to complete configurations (13%), $t(14) = 3.01$, $p = .009$, $d = .78$, 95% CI [.19, 1.35]. The partially grouped configuration exhibited an intermediate AB amplitude (20%), but this did not differ from the ungrouped ($p = .67$) or complete ($p = .29$) configurations.

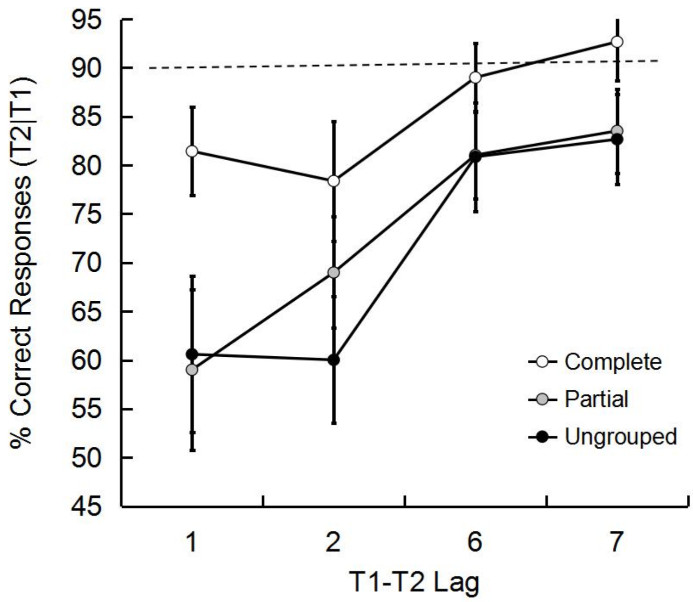


**Figure 4.** Mean percentage of correct identifications of T2 (given a correct T1 response) in Experiment 2. Correct identifications are presented as a function of the temporal lag from the onset of T1 to the onset of T2, separately for the different conditions (complete, partially grouped, and ungrouped configurations). The dashed horizontal line indicates the level of overall T1 accuracy. Error bars indicate 95% within-subject confidence intervals.

***T1-T2 pointing direction.*** In a subsequent analysis, we examined whether the (up-/downward) pointing direction of the partially grouped triangle in T1 influenced the detection performance for the (up-/downward pointing) T2 in partially grouped configurations. Figure 5B presents T2 accuracy as a function of lag, separately for the same and different orientations of the Kanizsa triangles. A two-way repeated-measures ANOVA of correct T2 responses with the factors T1–T2 direction (same, different) and lag (1, 2, 6, 7) revealed all main effects to be significant: T1–T2 direction, $F(1, 14) = 47.83$, $p < .0001$, $\eta_p^2 = .77$, 90% CI [.52, .85] and lag, $F(3, 42) = 14.05$, $p < .0001$, $\eta_p^2 = .50$, 90% CI [.28, .60]. T2 accuracy was higher for matching than for mismatching pointing directions (80% vs. 65%). T2 accuracy increased with T1–T2 lag, as described above. The interaction was also significant, $F(3, 42) = 3.08$, $p = .038$, $\eta_p^2 = .18$, 90% CI [.00, .30]: the accuracy difference between matching and mismatching pointing directions was reliable for the first three lags ($p$s < .003), but no longer reliable (i.e., reduced) at lag 7 ($p = .07$). Thus, in Experiment 2, the orientation similarity of the (Kanizsa) triangles modulated performance.

An analogous analysis was also performed for Experiment 1 (Figure 5A), comparing the same/different pointing direction of the T1 pacmen and the subsequent

T2 triangle configuration. This analysis revealed only a significant main effect of lag, $F(3, 42) = 17.11$, $p < .0001$, $\eta_p^2 = .55$, 90% CI [.34, .64], illustrating the AB effect pattern already described above (for Experiment 1). The fact that there was no effect of the same/different pointing direction at any lag (all $ts(14) < 1.35$, $ps > .20$; see Figure 5A) means that, in contrast to Experiment 2, there was no influence of the local pacman direction in T1 on the detection of T2 triangles in Experiment 1.

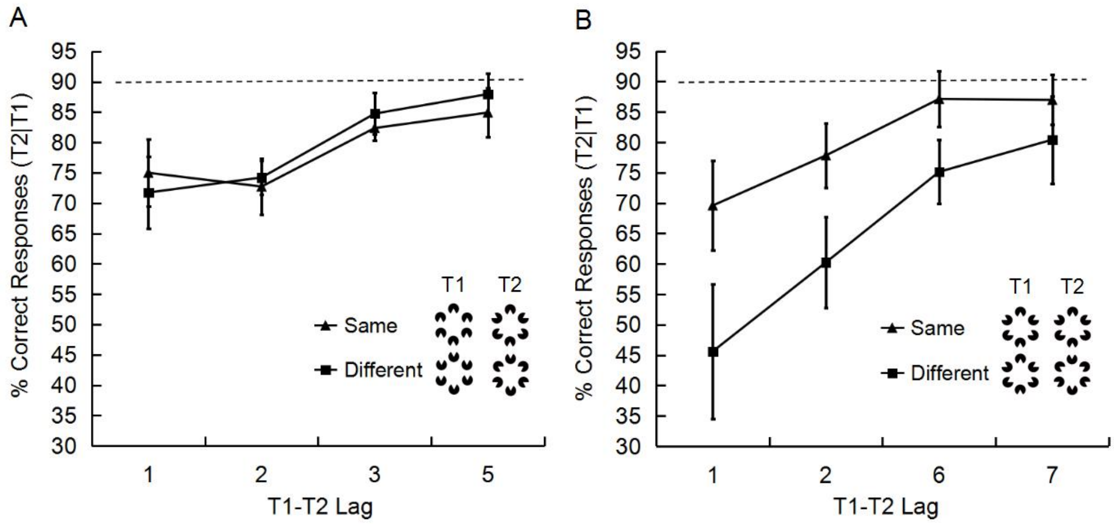


**Figure 5.** Mean percentage of correct identifications of T2 (given a correct T1 response) in Experiment 1 (A) and in Experiment 2 (B). Correct identifications are presented as a function of the temporal lag from the onset of T1 to the onset of T2, separately for same (matching) and different (mismatching) T1–T2 pointing directions (where T2 presented a Kanizsa triangle with up- or downward pointing direction). The dashed horizontal line indicates the level of overall T1 accuracy. Error bars indicate 95% within-subject confidence intervals.

***Cross-experiment comparison.*** To compare the AB amplitude between the two experiments, a mixed-design ANOVA with the within-subject factor T2-target type (complete, ungrouped) and the between-subject factor Experiment (1, 2) was performed. This analysis revealed a significant main effect of T2-target type, $F(1, 28) = 15.25$, $p < .001$, $\eta_p^2 = .35$, 90% CI [.12, .52], with an overall larger AB amplitude for ungrouped (19%) than for complete (10%) T2 configurations. There was also a marginally significant main effect of Experiment, $F(1, 28) = 3.12$, $p = .08$, $\eta_p^2 = .1$, 90% CI [.00, .28], reflecting a somewhat larger AB amplitude in Experiment 2 (18%) than in Experiment 1(11%). The interaction was not significant ($F < 1$, $p > .8$).

***T1 accuracy.*** Accuracy of T1 identifications was again relatively high, with an average of 90% correct responses, comparable to T1 performance in Experiment 1,

$t(28) = .33$, $p = .75$, $d = .12$, 95% CI [-.60, .84]. A two-way repeated-measures ANOVA with the factors T2-target type (complete, partially grouped, ungrouped) and lag (1, 2, 6, 7) only revealed a significant main effect of lag, $F(3, 42) = 13.60$, $p < .0001$, $\eta_p^2 = .49$, 90% CI [.27, .60]), with accuracy being reduced at lag 1 (86%, 90%, 93%, and 92% for lags 1, 2, 6 and 7; *p*s < .003), comparable to the finding in Experiment 1. There were no other significant effects (*F*s < 1, *p*s > .35).

### *Discussion*

The results of Experiment 2, in general, replicate those of Experiment 1, in that performance was overall reduced and the AB amplitude was larger for ungrouped relative to complete-object T2 configurations. Moreover, a comparison between Experiments 1 and 2 showed that increasing the strength of the T1 grouping translated into a somewhat increased AB overall. This pattern suggests that the effect of grouping on T2 detection is largely independent of the perceptual structure of the T1 stimuli, even though increasing the salience of T1 (in the present experiment: from “ungrouped” arrangements of pacmen to a coherent illusory triangle) leads to an increased difficulty in the processing of T2, because of a prolonged dwell of attention on T1.

Despite the lag × T2-target type interaction, there was still a significant difference between the completed and ungrouped T2 at both shorter lags (*p*s = .0001) and longer lags (*p*s < .001), which mirrors the result pattern of Experiment 1. For instance, even with a T1–T2 separation of 840 ms (at lag 7), performance for the ungrouped T2 configuration was still reduced relative to performance for T1 (mean difference: -7.04; $p < .04$). By contrast, performance for the complete T2 was roughly comparable (if not, in fact, being somewhat higher compared) to performance for T1 (mean difference: 2.96; $p = .06$). This suggests that the reduced performance for the ungrouped T2 does not simply reflect the temporal dynamics of attentional selection, that is: a sustained difficulty in selecting T2 while being engaged with T1. Rather, this constant difference across groupings might point to a difference in the efficiency with which the ungrouped vs. the complete T2 is retained at a post-selective stage in short-term memory until the execution of the response.

A second influence of T1 processing on T2 performance was revealed by the analysis of the same/different triangle pointing directions across the T1 and T2 (partially grouped) targets: accuracy was higher for T2 when the T2 triangle orientation matched that of T1, while accuracy was lower when they mismatched. No analogous effect was obtained in Experiment 1, in which the pacmen's local orientation and the global orientation of the triangle grouping could repeat across T1 and T2. This finding is consistent with Raymond's (2003) report of a same-object benefit for identical T1 and T2 stimuli (see also Conci & Müller, 2009). Our results mirror these previous findings and further show that repeated perceptual objects (Experiment 2), rather than repeated response-defining features (Experiment 1), lead to a reduction of the AB. Note that repeating the perceptual objects from T1 to T2 led to an attenuation but not a complete absence of the AB. This "residual" AB might have resulted from the change in task demands from T1 to T2 (see Visser, Bischof, & Di Lollo, 1999).

It should be noted that performance for the "different" (up-/downward pointing direction) condition was relatively low (65%), which may, to some extent at least, be attributable to a variant of "accidental" binding (Akyürek et al., 2012; see also Karabay & Akyürek, 2017). On this account, the presentation of two triangles pointing in opposite directions might yield the erroneous percept of a single Kanizsa star, integrating the sequential triangles into a unitary configuration. Such erroneous bindings would be particularly prominent at short temporal lags. To examine for this, we computed the frequency of participants reporting an integrated percept (i.e., a Kanizsa star) for the partially grouped target, given different T1 and T2 orientations. Indeed, erroneous Kanizsa star reports were rather frequent at lag 1 (36%), and declined at longer lags (21%, 13%, and 11% for lags 2, 6, and 7, respectively), revealing a linear trend: $F\ (1, 14) = 15.36$, $p = .002$, $\eta_p^2 = .52$, 90% CI [.17, .69]. This is consistent with observers tending to merge the two opposite triangles presented in succession into a single, coherent representation – consistent with the notion of "misbinding". For the "same" condition, by contrast, the erroneous star reports were significantly reduced (compared to the "different" condition), $F\ (1, 14) = 23.50$, $p < .0001$, $\eta_p^2 = .63$, 90% CI [.29, .75], revealing overall comparable rates of erroneous star reports across lags (12%, 11%, 9%, and 8% for lags 1, 2, 6, and 7, respectively, $p$s > .28).

## Experiment 3

In the experiments presented so far, participants were not only passively exposed to variants of Kanizsa figures (with varying grouping strength), but they were also required to actively classify these configurations, that is, to report the number of triangles presented in T2. Both experiments demonstrated a comparable pattern of results, namely a diminished AB and enhanced performance across lags when T2 presented a complete (as opposed to an ungrouped) configuration. This pattern was obtained regardless of the type of object presented as T1, suggesting some automaticity in processing the grouped object. Experiment 3 was performed to further elucidate how the specific task to classify a given object configuration in T2 determined the grouping effect. To investigate this issue, in Experiment 3, the T2 task was changed such that the requirements were unrelated to the object configuration presented. This was achieved by adding a small arrow (an oriented ">"-sign) to the (complete, partially grouped, or ungrouped) T2 configuration, and the T2 task was to report the orientation of the unrelated arrow (see Figure 6). If grouping does require top-down attention, then the change of the task requirements (in Experiment 3) should eliminate the above AB modulation of grouping (as attention does no longer need to be paid to the grouping, but only to the task-relevant arrow). By contrast, if grouping engenders automatic, early perceptual processing, then one would expect that the T2 accuracy would still be modulated by the (in Experiment 3) entirely task-irrelevant groupings.

### *Method*

Experiment 3 was similar to Experiment 1, except that the (complete, partially grouped, or ungrouped) T2 configuration was now presented for 70 ms, after which a small arrow (0.5° × 0.5°) was added to the RSVP stream for another 30 ms (see Figure 6). As in Experiment 1, the presentation of the stimuli was followed by a 20-ms blank interval, yielding a 120-ms SOA as in Experiments 1 and 2. The T2 task was to report the up/down/left/right pointing direction of the arrow, which was randomly presented at three possible locations within a given configuration (i.e., at top-left, top-right, or bottom locations; see Figure 6). Participants responded with a left-hand button press via keyboard, pressing the corresponding up-, down-, left-, or rightward-pointing arrow key, respectively. On a given trial, T1 was randomly allocated to one of three temporal serial positions, from 2 to 4, within a stream of 12 configurations. T2 was then presented at one of four different temporal lags (120, 240, 720, or 840 ms, corresponding to serial lag positions 1, 2, 6, or 7) subsequent to T1 (i.e., the lags were the same as in Experiment 2). RSVP stream distractors continued to be presented during the lag and after T2. The T1 target and task and the distractors remained the same as in Experiment 1. Fifteen right-handed volunteers (7 males; mean age: 23.67 ± 2.66 years) with normal or corrected-to-normal visual acuity participated in the experiment for payment of 8.00 Euro per hour. Each participant completed 24 practice plus 480 experimental trials (divided into 20 blocks).

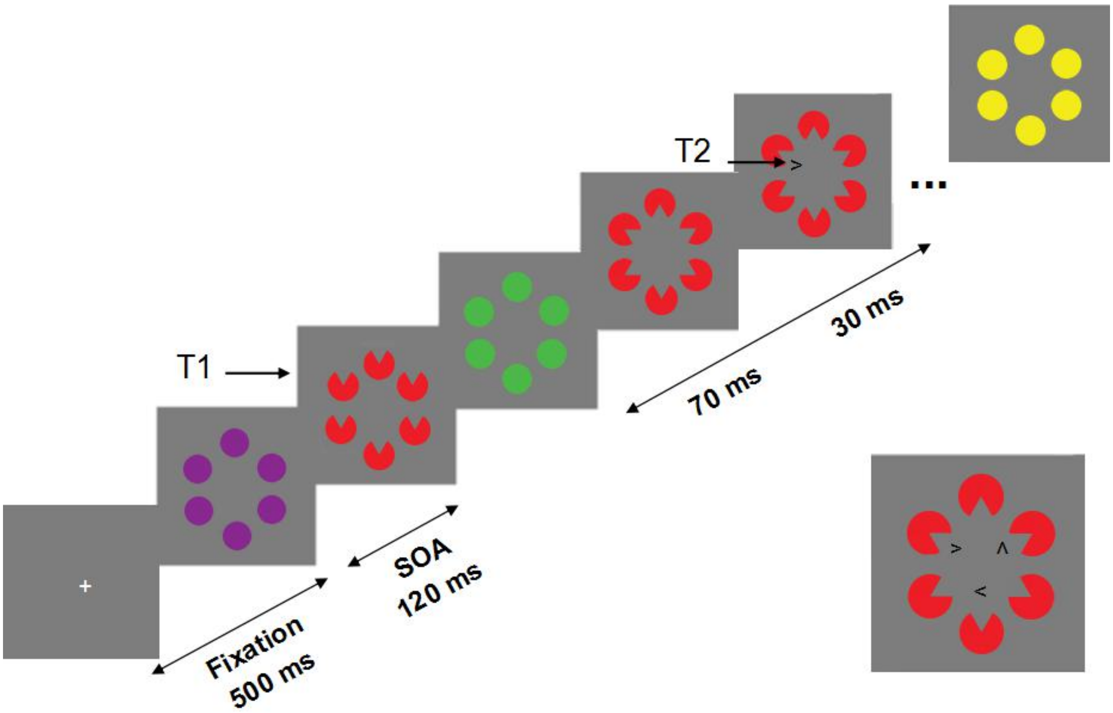


**Figure 6.** Schematic example of the RSVP sequence in Experiment 3. Each trial presented a sequence of 12 displays, which consisted of either six complete distractor disks (non-red items) or the T1 and T2 target. For T2, a complete, partially grouped, or an ungrouped configuration was presented (as in Experiment 1), but with an additional target arrow (i.e., an oriented ">"-sign) added to the display. Note that the T2 task was related only to the arrow (but not in any way to the Kanizsa-type configuration) presented. The bottom right panel illustrates all possible locations of the target arrow.

### *Results*

***T2 accuracy.*** Figure 7 presents the T2 accuracy (given a correct T1 response) as a function of lag, separately for the different target type conditions. A two-way repeated-measures ANOVA of correct T2 responses, with the factors T2-target type (complete, partially grouped, ungrouped) and lag (1, 2, 6, 7), revealed both main effects to be significant: T2-target type, $F(2, 28) = 5.40$, $p = .01$, $\eta_p^2 = .28$, 90% CI [.04, .44], and lag, $F(3, 42) = 12.00$, $p < .0001$, $\eta_p^2 = .46$, 90% CI [.24, .57]. There was a graded effect of target type, with the highest accuracy for ungrouped configurations (96%), followed by partially grouped (95%) and complete (94%) configurations (complete vs. ungrouped: $p = .02$; partially grouped vs. ungrouped: $p = .40$; partially grouped vs. complete: $p = .29$). In addition, there was a monotonic increase in performance from lag 1 onwards (92%, 94%, 97%, and 98% for lags 1, 2, 6, and 7, respectively; $p$s < .017, except for comparable performance with lags 6 and 7, $p = .56$). The T2-target type × lag interaction was also significant, $F(6, 84) = 2.25$, $p = .046$, $\eta_p^2 = .14$, 90% CI [.00, .20]: the AB amplitude (lag 1 vs. 6/7) was larger for complete (8%) compared to ungrouped configurations (4%), $t(14) = 4.20$, $p = .001$, $d = 1.09$, 95% CI [.43, 1.72]. Partially grouped configuration (5%) exhibited a marginal difference relative to complete configurations ($p = .067$), but did not differ from ungrouped configurations ($p = .61$). Thus, the AB was significantly modulated by grouping strength. However, importantly, this grouping modulation occurred in the reverse order compared to, for instance, Experiment 1, with the complete T2 configuration now leading to the strongest (rather than the smallest) AB.

***T1 accuracy.*** The mean percentage of correct responses for T1 was 97%. A two-way repeated measures ANOVA with the factors T2-target type (complete, partially grouped, ungrouped) and lag (1, 2, 6, 7) revealed only a lag effect, $F(3, 42) = 15.71$, $p < .0001$, $\eta_p^2 = .53$, 90% CI [.31, .63]: T1 performance was somewhat reduced at lag 1 (95%; $p$s < .005), while being comparable for lags 2, 6, and 7 (98%, 98%, and 99%, respectively; $p$s > .83). No main or interaction effect involving T2-target type was revealed ($F$s < 1.4, $ps$ > .23).

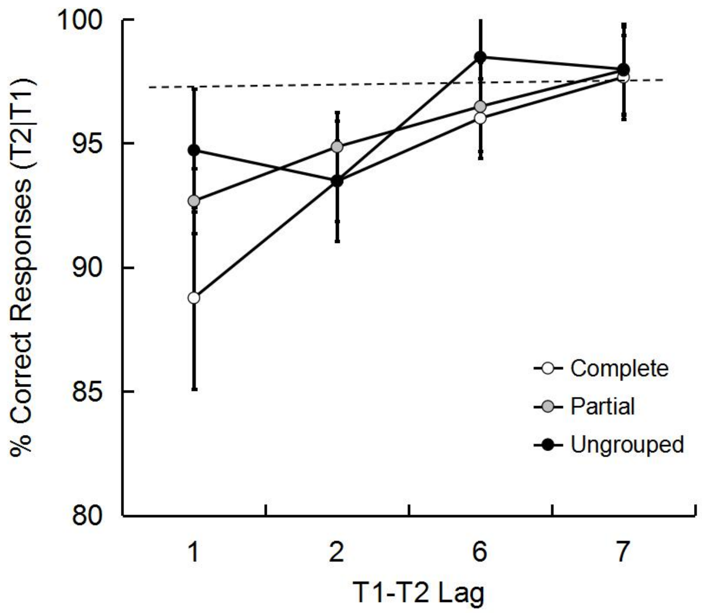


**Figure 7.** Mean percentage of correct identifications of T2 (given a correct T1 response) in Experiment 3. Correct identifications are presented as a function of the temporal lag from the onset of T1 to the onset of T2, separately for the different T2-target conditions (complete, partially grouped, and ungrouped configurations). The dashed horizontal line indicates the level of overall T1 accuracy. Error bars denote 95% within-subject confidence intervals.

### *Discussion*

Experiment 3 again demonstrated a graded effect of T2 grouping on the AB, indicating that, especially at short lags, discrimination of the arrow target (orientation) was substantially influenced by the surrounding object configuration. Thus, grouping does modulate performance, in particular when resources are occupied by T1-related processing. However, in contrast to Experiments 1 and 2, the effect of T2 configuration was reversed, with the smallest AB for ungrouped, an intermediate AB for partially grouped, and the largest AB for complete T2 configurations. This reversed AB pattern suggests that grouping, rather than being beneficial for the arrow discrimination task, did actually impair performance. An explanation for this pattern might be that attention was automatically captured by the task-irrelevant complete-object configuration, and as a result discrimination of the target orientation was hampered. Ungrouped T2 configurations, by contrast, attracted attention less and, consequently, more resources were available for the effective discrimination of the arrow target. In addition, unlike in the previous two experiments, T2 performance clearly reached the level of T1 accuracy at lag 7 (i.e., after 840 ms), for all types of configuration. This indicates that a task-irrelevant grouping may influence the efficiency of attentional target selection, thus modulating the AB primarily at short lags. However, the fact that this modulation was rather transient suggests that, in Experiment 3, grouping did not affect short-term memory consolidation (i.e., post-selective, stage-2 processing) of the T2 target.

## General Discussion

The AB phenomenon demonstrates that the human visual system is limited in its ability to extract durable mental representations from the rapidly changing, continuous flow of information across time. The present study investigated whether the AB effect is modulated by perceptual grouping in Kanizsa subjective figures, using a dual-target RSVP paradigm – the aim being to determine how attention is allocated to more or less structured visual information over time. The results showed that the AB effect is strongly modulated by T2 grouping strength: In Experiment 1, complete T2 groupings resulted in a smaller AB and in a reduced overall performance compared to ungrouped (control) stimuli that consisted of the same pacman inducers which did, however, not induce an integrated percept. Experiment 2 replicated this pattern of results and further showed that the benefit of grouping in T2 can arise irrespective of the perceptual structure in T1 (Experiments 1 vs. 2). Finally, in Experiment 3, a modulation of grouping in T2 was obtained even though the task was entirely unrelated to the object configurations. In contrast to Experiment 1, performance in Experiment 3 revealed the largest AB when a T2 target was presented concurrently with a complete-object configuration. Together, this pattern suggests that the grouping either attenuates or enhances the AB, depending on whether grouping is task-relevant or not (Experiments 1 vs. 3).

### *Grouping modulates temporal object processing*

Why does grouping in T2 modulate the allocation of attention in time? According to the two-stage model (Chun & Potter, 1995), after initial perceptual processing of the incoming sensory information, the perceptual representation must be encoded in a capacity-limited short-term memory system to ensure a stable and durable representation until a response can be issued. If this consolidation process is not accomplished, the perceptually processed item is ephemeral and rapidly overwritten by the items that appear subsequently in the RSVP stream. In this view, the AB reflects a post-perceptual, attentional mechanism of limited processing capacity, which subserves the consolidation of items into working memory (Chun & Potter, 1995; Jolicœur & Dell'Acqua, 1998; Vogel et al., 1998). With salient items – for instance, grouped objects such as Kanizsa figures (Rauschenberger & Yantis, 2001; Senkowski et al., 2005) – a processing advantage should arise relatively early, at the initial stage of perceptual coding, with the global structure of grouped objects allowing for more efficient detection compared to configurations that lack a global representation (e.g., Conci et al., 2007a, 2009). That is, pre-attentive grouping would generate a salient structure that is more resistant to temporal decay at stage 1, thus providing more time for consolidation at the subsequent, capacity-limited processing stage. As a result of rather efficient detection of a grouped T2, consolidation at stage 2 can commence earlier and proceed faster, as compared to a less structured T2, in turn facilitating the maintenance of the grouped object in working memory (see, e.g., Chen et al., 2016; Chen, Töllner, Müller, & Conci, 2017, for a related finding). In support of this view, Experiments 1 and 2 consistently showed overall superior performance for grouped than for ungrouped T2s, even at longer lags when T2 processing was no longer affected by T1 processing. Moreover, the performance difference for grouped (vs. ungrouped) T2s was largest at short intervals (in all experiments), where capacity-limited resources were most likely occupied by processes relating to T1. This indicates that attentional limitations imposed by the AB can be overcome, to a significant extent, by grouping in the target, making processing more robust and more efficient in face of the lack of limited-capacity resources (Experiments 1 and 2).

However, it should be noted that – although grouping likely increased the coding efficiency of complete-object targets (i.e., it enabled consolidation to begin earlier and to require fewer attentional resources), which manifested in an attenuated AB (Experiments 1 and 2) – our results nevertheless reveled a clear AB for all grouping types. This might be taken to suggest that grouping of disparate items into a coherent whole nevertheless requires a certain amount of attentional resources in order to select and retain a relevant target item until the response is issued (Joseph et al., 1997; Braun, 1998; see also Gögler, Finke, Keller, Müller, & Conci, 2016). However, increasing the efficiency with which the stimulus is encoded (e.g., by inducing grouping) in turn reduces the attentional load and, consequently, reduces the AB (see also Braun, 1998; Joseph, Chun, & Nakayama, 1998).

Additional support for an early-processing account of grouped objects derive from the results of Experiment 2, in which T1 presented a partially grouped (triangle) object that was more effective in binding attentional resources than the ungrouped T1 in Experiment 1. While the global T1 triangle in Experiment 2 led to an overall increased AB effect (as compared to the local T1 configuration in Experiment 1), the modulation of grouping in T2 was unaffected by this change in T1. This further supports the view that the benefit of grouping occurs because salient perceptual structures by themselves allow for a more efficient encoding of the grouped configurations (rather than arising from some top-down mediated sharing of resources between T1 and T2). That is, grouping renders particularly stable perceptual representations that are resilient in the face of interfering stimulation when only limited resources are available.

Consistent with this view, in visual search tasks, Kanizsa figures can act as a (non-informative) spatial cue, or in terms of an attractor for spatial attention, that facilitates detection of a target appearing at the same, circumscribed location (Senkowski et al., 2005; Conci, Müller, & von Mühlenen, 2013). However, the results of the present Experiment 3 show that when a comparable setup is used in an AB paradigm, a cost associated with the grouped object is observed, rather than efficient cueing of attention to the arrow target. This may come about as a result of the rapid succession of the stimuli in the RSVP stream. The Kanisza-type configuration may act as a salient distractor (i.e., it may capture attention), from which attention must be disengaged in order to be able to discriminate the task-relevant arrow stimulus. However, by the time this is accomplished, the (briefly presented) target has already disappeared – resulting in a performance cost and in an increased AB. Of note, the task-irrelevant grouping modulated the detection of T2 primarily at short lags, whereas at longer lags T2 performance reached the same level as T1 performance, for all grouping types (complete, partially grouped, and ungrouped). This pattern contrasts with Experiments 1 and 2, in which (in these experiments) the task-relevant Kanizsa grouping not only modulated the immediate allocation of attention, but also the subsequent short-term memory consolidation of T2 at longer lags. This illustrates that task-irrelevant groupings can generate transient costs, whereas task-relevant groupings can yield sustained benefits.

### *Representing higher-order object files*

When processing multiple objects in rapid succession, a key requirement of the visual system is its ability to select and consolidate potentially relevant information into an enduring representation, referred to as an "object file" (Kahnemann & Treisman, 1984). Raymond (2003) proposed that the creation of a new object file plays a key role in triggering the AB (see also Kellie & Shapiro, 2004; Conci & Müller, 2009). In line with such an object file account, we observed superior performance for T2 identification and an attenuated AB when T2 was identical in shape to T1 (see Experiment 2). Since an object file has already been set up upon the presentation of T1, with a same-object T2, the identical object file needs only to be updated – as a result of which the AB is reduced. In addition, integration might arise when two targets provide complementary shapes in close temporal proximity, as evidenced by a significant drop in performance across lags for partially grouped T2s (i.e., when T1 and T2 present Kanizsa triangles of opposite orientations; see Experiment 2). In this case, a "star" representation was more likely reported for T2, indicative of some form of misbinding across T1 and T2. These findings support an integration account as proposed by Hommel and Akyürek (2005), which assumes that it is difficult to segregate a continuous, rapid stream of visual information into discrete events. In this view, the closer in time two pieces of information appear, the more likely they are integrated into the same episodic trace – a finding which has been demonstrated using various types of objects and groupings (Bowman & Wyble, 2007; Akyürek & Hommel, 2005; Akyürek et al., 2012; Karabay & Akyürek, 2017).

### *Conclusion*

Whereas perceptual grouping can modulate the allocation of selective attention across visual space, the present findings show that structures provided by grouping can also influence the processing of targets in time. For instance, grouped targets lead to overall enhanced performance and a reduced AB effect, where the benefits from grouping are sustained, suggesting that they arise at an early, perceptual locus prior to attentional selection, thus facilitating both the detection of integrated structures and their subsequent consolidation into an enduring object file. By contrast, grouping in task-irrelevant items can transiently impair concurrent target processing, where this cost (from complete-object distractors) may be attributed to attentional capture, hindering efficient selection of the target. Together, this set of findings shows that grouping can substantially modulate the processing of objects in time.

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## 2.3 Study 3: Amodal completion in visual working memory

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The author of this dissertation designed and programmed the experiments, collected and analyzed the data, created plots, interpreted the results and wrote the journal article.

Hermann Müller commented on and helped revising the manuscript.

Markus Conci conceived and supervised the project, participated in designing and programming the experiments and interpreting the results. He commented on and helped revising the manuscript.

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# Amodal Completion in Visual Working Memory

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Amodal completion refers to the perceptual "filling-in" of partly occluded object fragments. Previous work has shown that object completion occurs efficiently, at early perceptual stages of processing. However, despite efficient early completion, at a later stage, the maintenance of complete-object representations in visual working memory (VWM) may be severely restricted due to limited mnemonic resources being available. To examine for such a limitation, we investigated whether the structure of to-be-remembered objects influences what is encoded and maintained in VWM using a change detection paradigm. Participants were presented with a memory display that contained either "composite" objects, that is, notched shapes abutting an occluding square, or equivalent unoccluded, "simple" objects. The results showed overall increased memory performance for simple relative to composite objects. Moreover, evidence for completion in VWM was found for composite objects that were interpreted as globally completed wholes, relative to local completions or an uncompleted mosaic (baseline) condition. This global completion advantage was obtained only when the "context" of simple objects also supported a global object interpretation. Finally, with an increase in memory set size, the global object advantage decreased substantially. These findings indicate that processes of amodal completion influence VWM performance until some overall-capacity limitation prevents completion. VWM completion processes do not operate automatically; rather, the representation format is determined top-down based on the simple object context provided. Overall, these findings support the notion of VWM as a capacity-limited resource, with storage capacity depending on the structured representation of to-be-remembered objects.

*Keywords:* amodal completion, visual working memory, mnemonic resources, context, capacity



Visual environments provide a cluttered and complex input to the visual system, which must be structured, that is, perceptually grouped into coherent patterns or wholes to support object recognition and visually guided actions. Under natural viewing conditions, many objects in our ambient array are partly occluded by other objects. These occlusion relationships, however, do not result in a percept of fragmented objects; instead, we usually perceive a world that is made out of coherent wholes. For example, in a visual scene, flowers may be hidden behind trees, while a house may in turn occlude parts of the trees. Despite these partial occlusions, we do not perceive the flowers as floating in the air or the trees as having house-shaped holes. Instead, the environment appears to consist of complete objects, and we do almost never experience any ambiguities. The phenomenon that occluded parts are perceptually "filled in" has been referred to as amodal completion (Michotte, Thines, & Crabbe, 1964/1991), that is, completion in face of the partial absence of physical stimulation.

Two different types of completion have been proposed to account for how people complete partly occluded objects. In global completion, the symmetry of a completed shape is maximized (Sekuler, Palmer, & Flynn, 1994; Van Lier, Leeuwenberg, & Van der Helm, 1995); local completion, by contrast, comprises a "good" (e.g., linear) interpolation of the occluded contours, yielding an integrated object based on the shape's boundaries (Fantoni & Gerbino, 2003; Kellman & Shipley, 1991). Previous studies have shown that global completion is usually the predominant mode for partly occluded objects (e.g., De Wit & Van Lier, 2002; Sekuler, 1994; Sekuler et al., 1994; Van Lier, 1999, 2001; Van Lier & Wagemans, 1999). However, in addition to global and local completion interpretations, partly occluded objects could also be interpreted as an uncompleted two-dimensional "mosaic" figure. That is, a mosaic interpretation would be the most basic one, simply taking the visible input as a default: the figure is simply represented in terms of the visible, "cut-out" segments that adjoin one another, without considering that parts of the object may be occluded. Figure 1 provides several examples of global, local, and mosaic completions, illustrating that every partly occluded figure may give rise to different complete-object or corresponding mosaic interpretations.

A number of studies employed visual search paradigms to investigate whether integrated object representations are available preattentively. For instance, it has been shown that visual search for a partly occluded target is guided by a complete-object representation (Davis & Driver, 1998; He & Nakayama, 1992; Rensink & Enns, 1998). For example, in Rensink and Enns (1998), participants searched for a notched disk target among complete disks and squares. In a condition in which the notched target disk abutted a square (adjacent condition), the search turned out inefficient—because, so the explanation, the notched target is rendered similar

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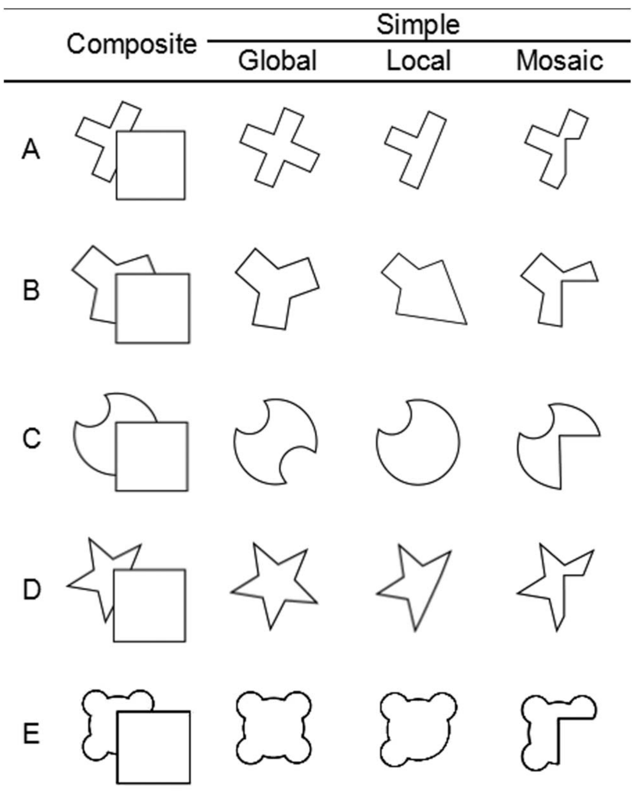


*Figure 1.* Illustration of experimental stimuli with their respective composite and simple versions (global, local completion, and mosaic interpretation), adapted from Van Lier et al. (1995), Plomp and Van Leeuwen (2006), and Sekuler et al. (1994).

to the complete distractor disks by amodal completion. In contrast, search was efficient when the target was spatially separated from the neighboring square; in this (separate) condition, completion does not occur—thus supporting more efficient search. Results such as these have been taken to indicate that visual search relies on complete-object representations (see also Conci, Müller, & Elliott, 2007a, 2007b, 2009), with (amodal) completion occurring rather automatically, that is, prior to the engagement of attention (Conci et al., 2009; Mattingley, Davis & Driver, 1997). However, Rauschenberger and Yantis (2001), in a follow-on study, combined a search task with a masking procedure to interrupt visual processing. Given sufficient time prior to masking, the previous results were replicated, that is: There was evidence of amodal completion in the adjacent condition, but not in the separate condition. By contrast, when the masks were presented relatively early (<200 ms), search was comparable in efficiency between the separate and adjacent conditions, indicating that, under these conditions, amodal completion was prevented with the adjacent configuration. This outcome suggests that completion goes through distinct stages and that an initial, "mosaic" stage may precede completion (see also Plomp, Liu, Van Leeuwen, & Ioannides, 2006; Sekuler & Palmer, 1992).

Taken together, these findings indicate that completed objects are processed rather efficiently, with sequential perceptual stages rendering completed objects starting from a simple, default "mosaic" interpretation. However, at an even later stage of processing, the encoding and maintenance of object representations in visual working memory (VWM) may be tightly restricted due to the limited availability of mnemonic resources (Jolicoeur & Dell' Acqua, 1998; Thorpe, Fize, & Marlot, 1996; Vogel, Luck, & Shapiro, 1998; Woodman, Vogel, & Luck, 2001). Here, we investigated whether the structure of to-be-remembered objects influences what is encoded and maintained in VWM.

Specifically, in this study, we were interested in whether completion is reflected in memory capacity. Luck and Vogel (1997) showed that VWM can roughly store about four items, irrespective of the number of features that the objects are composed of; restated, VWM may be conceived of as providing about four "slots," permitting up to four complete objects to be represented irrespective of their complexity. However, subsequent evidence indicated that VWM capacity in fact also depends on visual information load, rather than reflecting just the number of objects currently held in VWM. For example, Alvarez and Cavanagh (2004) attempted to characterize the visual information load of different objects categories (such as shaded cubes, Chinese characters, and colored squares) in terms of the search efficiency afforded by each object category in a simple visual search task (under conditions of varying search display sizes). The assumption was that search efficiency (i.e., the slope of the function relating display size to response latency) would reflect the perceptual complexity of a given object category. In a subsequent experiment, the same objects were presented in a change detection task, which required participants to remember a set of objects in an initial memory display. Then, following a brief delay, a test display was presented which required participants to determine whether one of the presented objects, which were all of the same category, had changed. The results revealed a strong linear relation between the number of items that can be stored in VWM (as assessed in the change detection task) and the visual information load of these items (as determined by the slope of the search function). According to this logic, if a completed object is represented in VWM, memory capacity should be affected, because postcompletion representations give rise to a greater visual information load (as evidenced by steeper slopes) in visual search studies compared to uncompleted objects (Davis & Driver, 1998; He & Nakayama, 1992; Rensink & Enns, 1998). Following this line of reasoning, we hypothesized that completion requires mnemonic resources, that is: completed objects require more VWM capacity to be maintained, leading to reduced memory performance if capacity is exceeded.

To test this idea, we employed a change detection paradigm (Luck & Vogel, 1997) in which participants were presented with a memory display that contained composite objects (i.e., a notched-figure adjacent to a square) or simple objects (i.e., possible interpretations of the composite objects without the adjacent square, see Figure 1). After a brief delay, a simple object probe appeared, presenting one possible interpretation at one of the locations that had previously been occupied by an item in the memory display. The task was to decide whether the probe item was the same as or different from the object presented beforehand at the same location in the memory display (see Figure 2 for an example). This variant of the change detection task with composite objects as to-be-remembered items was intended to permit assessment of whether or not the mechanisms of (amodal) object completion require

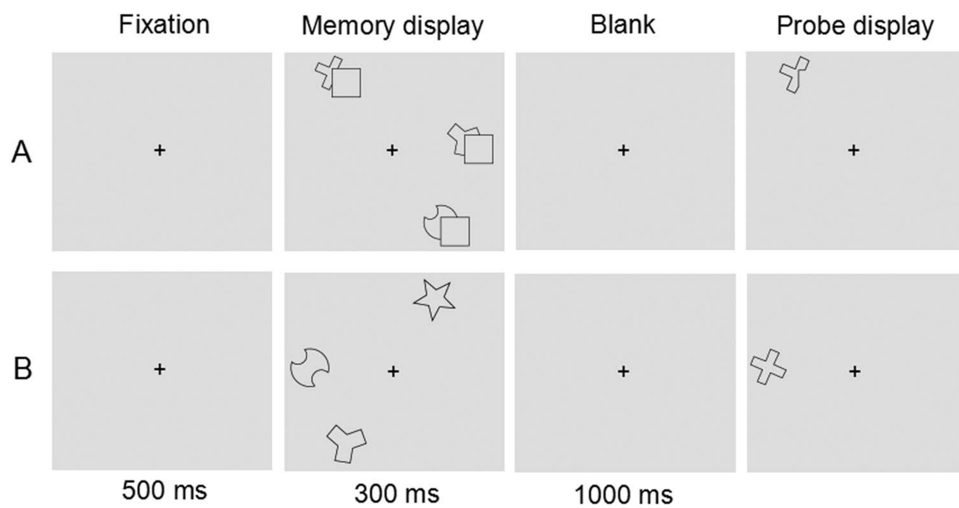


*Figure 2.* Experimental procedure. Panel A shows an example trial presenting a composite-object memory display followed by a probe supporting a mosaic interpretation. The correct response would be "same." Panel B depicts an example trial with a simple-object memory display, presenting global completions. The correct response would be "different."



resources in VWM beyond those needed to represent objects that are not completed behind an occluder.

## Experiment 1

Experiment 1 was performed to investigate the role of object completion in VWM, by assessing memory capacity for composite and simple objects, with the former giving rise to amodal completion. We employed a change detection paradigm (Luck & Vogel, 1997). Participants were randomly presented with a memory display of simple or composite objects for 300 ms, and after a brief delay, a probe item appeared (see Figure 2). The task was to decide whether the probe was the same or different relative to the object presented previously at the same location in the memory display. The presentation time of the memory display was set in accordance with previous studies (Sekuler et al., 1994), to ensure that completion could take place within the time allowed. If completion occurs and requires mnemonic resources, then performance was expected to differ for completed relative to uncompleted objects.

### Method

**Participants.** Sixteen right-handed volunteers (nine female, seven male) with normal or corrected-to-normal vision participated in Experiment 1. Their ages ranged from 18 to 30 years (mean age = 25.25 years). All participants were naive as to the purpose of the study. They participated in the experiment for payment of €8.00 per hr. All participants provided written informed consent, and the experimental procedure was approved by the ethics committee of the Department of Psychology, Ludwig-Maximilians-University Munich.

**Apparatus and stimuli.** The experiment was controlled by an IBM-PC compatible computer, running Matlab routines and Psychophysics Toolbox extensions (Brainard, 1997; Pelli, 1997). The stimuli were black line drawings (0.2 cd/m$^2$) against a gray background (178 cd/m$^2$), presented on a 17-inch computer monitor (1,024 × 768 pixel screen resolution, 85-Hz refresh rate). The experiment was conducted in a sound-attenuated room that was dimly lit.

The complete stimulus set is shown in Figure 1. The stimuli used in Experiment 1 were adapted from previous studies (Plomp & Van Leeuwen, 2006; Van Lier, Van der Helm, & Leeuwenberg, 1995); they are depicted in Figure 1A–D. As can be seen, they consisted of composite and simple objects. Each composite figure included a square with a second shape positioned partly occluded next to the square (Figure 1, Composite). The average amount of occlusion was 30% across all occlusion interpretations. Every simple figure was presented in three variants, corresponding to the three possible alternative interpretations of the composite object: global completion, local completion, and mosaic (see Figure 1, Simple—Global, Local, Mosaic, respectively). Global completions presented a symmetrical shape interpretation of the occluded object, whereas a local completion was based on the linear continuation (interpolation) of the visible parts of the occluded shape. A mosaic figure simply presented a two-dimensional (2-D) cut-out outline shape identical to the visible part of the partly occluded figure. The widest aspect of each simple object touched the borders of a circular region with a diameter of 2.4° of visual angle. The square of the occluded objects subtended 2.1° × 2.1° of visual angle. For each memory display, three distinct objects (from the same completion condition) were presented randomly at six positions within a circular region subtending 12.4° of visual angle.

**Procedure and design.** Each trial started with the presentation of a central fixation cross for 500 ms. Next, participants were randomly presented with a memory display of simple or composite objects for 300 ms. Following a blank screen of 1,000 ms, a simple figure probe (global, local, or mosaic) appeared at one of the locations that had previously been occupied by an item in the memory display. The probe display remained visible until participants responded. Participants responded with the left and, respectively, right mouse keys to indicate whether the probe object was the same as or different from the object at the same location in the previous, memory display. Note that "same" or "different" in this experiment refers to object identity, rather than to the completion type. For example, the occluded cross in Figure 1A (Composite) would be considered the same object in relation to all other simple objects that present a cross-shaped item (Figure 1A, Simple). The objects in a given memory display were randomly selected from the available set of stimuli, with the constraint that all objects were of the same completion type (i.e., global, local, or mosaic, respectively) and no object repeated in the same display. It should be noted that different completion types were presented in separate parts of the experiment, such that, for a given experimental part, all simple objects in the memory and probe displays would coherently support the same (global, local, or mosaic) object interpretation. Thus, blocking by completion type ensured that observers could generate a coherent interpretation in a consistent manner, potentially maximizing effects of amodal completion in the current experiment (see Albright & Stoner, 2002; Liu, Plomp, Van Leeuwen, & Ioannides, 2006; Plomp et al., 2006; Plomp & Van Leeuwen, 2006; Rauschenberger, Peterson, Mosca, & Bruno, 2004). Observers were asked to respond as accurately as possible; there was no stress on response speed. In case of an erroneous response, feedback was provided in the form of an "alerting" sign ("–") presented for 1,000 ms at the center of the screen. Trials were separated from each other by an interval of 1,000 ms. Figure 2 illustrates typical examples of a trial sequence.

A within-subjects design was used. The independent variables were object configuration (simple or composite objects in the memory display), interpretation (global completion, local completion, or mosaic interpretation), and change in the probe display (yes, no). The experiment was subdivided into three parts, with each part displaying one type of possible interpretation. Thus, each part of the experiment presented only one type of (simple) object (i.e., global, local, or mosaic figure) in the memory and probe displays to enforce a corresponding interpretation of the composite (occluded) objects within a given experimental part (e.g., Albright & Stoner, 2002). The three parts were presented in random order. Within each part, the different configurations (simple, composite) and change and no-change trials were presented in randomized order across trials. There was one initial block of 12 practice trials, followed by four experimental blocks of 42 trials per part, yielding 504 experimental trials in total.

## Results

The primary dependent variable was $d'$, to examine participants' ability to distinguish change from no-change trials regardless of any bias to respond "change" or "no change" within the Signal Detection Theory framework (Green & Swets, 1966).[1] The sensitivity index $d'$ is calculated as z (proportion hits) − z (proportion false alarms), with a hit defined as correct detection of a change and a false alarm as a "change" response in the absence of an actual change. Extreme, "perfect" scores were adjusted using the following formulas: $1–1/(2n)$ for hit rates of 100%, and $1/(2n)$ for zero false alarms, where $n$ refers to the number of total hits or false alarms (Macmillan & Creelman, 1991).

Figure 3 presents the mean $d'$ scores as a function of simple and composite object configurations in the memory display, separately for different interpretations. In addition, mean accuracy scores are

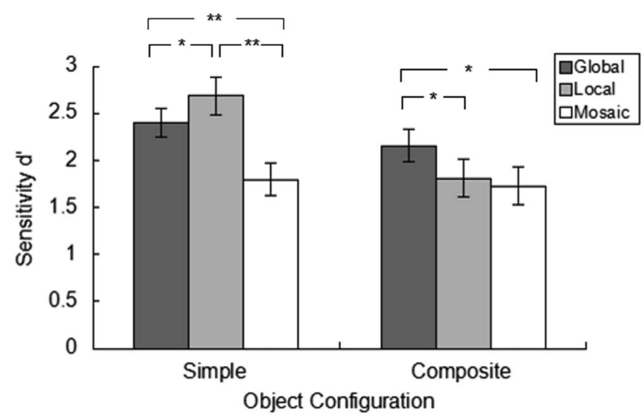


*Figure 3.* Mean change detection sensitivity, $d'$, as a function of the object configuration (simple, composite) in the memory display, separately for the different interpretations (global, local, mosaic) in Experiment 1. Error bars denote 95% (within-subject) confidence intervals. Significant differences revealed by pairwise comparisons are indicated by asterisks. $^{*}\ p < .05$. $^{**}\ p < .001$.

provided in Table 1 (for all three experiments presented). A repeated-measures ANOVA on the $d'$ scores, with object configuration (simple, composite) and interpretation (global, local or mosaic) as within-participants factors, revealed a main effect of object configuration, $F(1, 15) = 29.25$, $p < .0001$, $\eta_p^2 = .66$, with higher sensitivity for simple ($d' = 2.30$) than for composite ($d' = 1.90$) objects, and a main effect of interpretation, $F(2, 30) = 9.92$, $p < .0001$, $\eta_p^2 = .40$, with higher sensitivity for global and local completion as compared with the mosaic interpretation (2.28, 2.25, and 1.76 for the global, local, and mosaic interpretations, respectively; all $ps < .01$). Importantly, there was also a significant interaction between object configuration and interpretation, $F(2, 30) = 18.57$, $p < .0001$, $\eta_p^2 = .55$, owing to the fact that sensitivity was highest for local, intermediate for global, and lowest for mosaic variants of simple objects (all $ps < .05$). By contrast, for composite objects, $d'$ was higher for global as compared with both local and mosaic interpretations (all $ps < .05$).

## Discussion

The results of Experiment 1 demonstrate that performance was overall lower for composite relative to simple objects. Moreover, the different variants of each stimulus also affected performance: Simple objects were associated with an increase in performance (i.e., in sensitivity) from mosaic through global to local objects. By contrast, for composite objects, the global completion interpretation exhibited the highest sensitivity score compared to the local completion and mosaic interpretations.

Note that, when comparing the various interpretations of composite with the corresponding simple objects, for the mosaic interpretation, sensitivity for the visible parts in composite (mosaic) objects was essentially equivalent to that with (physically identical) cutout segments in simple objects ($p = .52$)—indicating that

[1] Analyses of percent correct scores and capacity estimates $K$ (Cowan, 2001) were also performed on all reported data. These analyses revealed identical patterns of results to that using $d'$, in all three experiments.

Table 1
*Mean Accuracies (Proportion Correct) in Experiments 1–3 for all Stimulus Conditions*

| | | Simple | | | Composite | | |
|---|---|---|---|---|---|---|---|
| Experiment | Set size | Global | Local | Mosaic | Global | Local | Mosaic |
| 1 | 3 | .86 | .88 | .79 | .83 | .79 | .78 |
| 2 | 3 | .82 | .85 | .77 | .76 | .78 | .77 |
| 3 | 2 | .93 | | .89 | .90 | | .86 |
| | 4 | .74 | | .71 | .72 | | .70 |

the encoding of the (task-irrelevant) square occluder in composite objects did not affect task performance. By contrast, global and local completion interpretations were associated with reduced sensitivity for composite relative to simple objects ($ps < .05$)—presumably attributable to amodal completion, which requires additional VWM resources beyond the "basic" representation of simple objects. It cannot be ruled out, though, that it also reflects differential shape discriminability among the to-be-remembered objects (see Awh, Barton & Vogel, 2007).

The effect of shape discriminability is most obvious when considering the pattern of results for simple objects: Mosaic shapes are the most complex ones of the set of stimuli presented, arguably making them difficult to represent and discriminate from each other, thus giving rise to the lowest change detection performance. Moreover, global shapes are presumably harder to memorize than local shapes, because global shapes are (by definition) more symmetric and overall less variable in their outline shapes, (see Figure 1), thus making it harder to maintain distinct representations of the presented objects. For instance, a local-object change (e.g., of the local "arrow" in Figure 1B into the local "T" shape in Figure 1A) might be more conspicuous than the very same change for the global set of objects (e.g., of the global "cross" in Figure 1A into the global "wind wheel" in Figure 1B), simply because the local changes on average involve a larger change in the size of the object compared to global changes. In this view, the differences in performance among the various simple objects can be taken to reflect the ease with which a given shape can be discriminated from other to-be-remembered shapes.

Direct evidence of amodal completion in VWM is revealed when comparing the various interpretations of the composite objects: The depicted shapes (for the various interpretations) are all physically identical and therefore are equally difficult to discriminate from each other. Despite identical shapes for each of the possible composite object interpretations, sensitivity was nevertheless substantially higher for global completions compared with all other object types sensitivity—indicating that observers were more sensitive to detect a change when a given shape could be amodally completed to form a global object, as compared with an identical, uncompleted mosaic shape. At the same time, however, the amodally completed shape required more VWM capacity than a comparable simple global shape that does not require to be completed behind the occluding square ($p < .05$, see above). In contrast, no benefit of amodal completion was evident when comparing composite local with composite mosaic objects. This pattern of results is essentially in line with findings from other approaches studying amodal completion in purely visual tasks without the specific engagement of VWM resources (e.g., De Wit & Van Lier, 2002; Sekuler, 1994; Sekuler et al., 1994; Van Lier, 1999, 2001; Van Lier & Wagemans, 1999). Taken together, these studies suggest that global completion is the default, or preferred, mode of interpretation by which partly occluded objects are completed. Thus, both perceptual analysis and mnemonic processing are governed by a tendency to maximize the symmetry of an occluded object (in the global completion interpretation), while completion on the basis of good continuity (in the local completion interpretation) is less likely to be employed.

It should be noted that our experiment presented simple and composite object displays blocked by object interpretation, that is, with separate experimental parts for global, local, and mosaic interpretations, respectively. Thus, in each part, the presented simple object shapes may have primed the processing of composite objects, and in fact it has been shown that the type of occlusion depends on the presented context (Liu et al., 2006; Peterson & Hochberg, 1983; Plomp et al., 2006; Plomp & Van Leeuwen, 2006; Rauschenberger et al., 2004). Thus, contextual information (i.e., the prevailing interpretation as afforded by the simple objects in a given part of the experiment) may be used to guide the encoding of the composite objects in VWM. In other words, the context provided by simple objects throughout a given part of the experiment might be regarded as "priming" an interpretation of the presented composite objects (Plomp & Van Leeuwen, 2006). As described above, such priming by the simple object context was particularly effective for global completions, while there was no comparable priming of local completions. Next, in Experiment 2, we set out to examine whether a global completion benefit in VWM would be replicable without an influence of context.

## Experiment 2

Experiment 1 revealed evidence for an effect of global object completion in VWM. Importantly, in Experiment 1, the different—global, local, and mosaic—interpretations as given by the simple objects in the memory and probe displays were presented in separate parts of the experiment. Accordingly, these simple objects provided some kind of consistent context within which the composite objects were interpreted. In Experiment 2, we investigated whether evidence for object completion in VWM would also be obtained in the absence of such a consistent context favoring a given interpretation throughout a block of trials. To this end, memory displays with simple and, respectively, composite objects were presented separately in different blocks (and interpretations, for composite objects now enforced only by the probe display, were presented in randomized order). That is, simple memory display objects were no longer available to support a consistent interpretation of the composite objects. If the interpretation of a given composite object is determined mainly by the context prevailing throughout a block of trials (as was the case in Experiment 1), then we would expect that, without such a consistent context, change detection for composite objects is comparable across the global, local, and mosaic interpretations.

## Method

Experiment 2 was largely identical to Experiment 1, with the following exceptions. We tested a new group of 16 right-handed paid volunteers (10 female, six male; mean age = 23.8 years; normal or corrected-to-normal vision). Simple and composite memory display objects were presented in different experimental blocks, whereas the different interpretations (which, for composite objects, were provided solely by the single simple object shown in the probe display) and change and no-change trials were presented in random order within each block. The experiment started with two blocks of 12 practice trials (presenting either simple or composite memory displays), followed by 20 experimental blocks of 24 trials each, amounting to 480 experimental trials in total. Participants were presented with the simple and composite blocks in randomized order.

## Results

A repeated-measures ANOVA with main terms for object configuration (simple, composite) and interpretation (global, local, or mosaic) revealed both main effects to be significant: object configuration, $F(1, 15) = 6.32$, $p < .05$, $\eta_p^2 = .30$; and interpretation, $F(2, 30) = 9.76$, $p < .001$, $\eta_p^2 = .39$. Sensitivity was significantly higher for simple ($d' = 1.92$) than for composite ($d' = 1.62$) objects, and higher for local than for global and mosaic interpretations ($d' = 1.96$, 1.73, and 1.62, respectively; all *p*s $< .05$). The interaction between object configuration and interpretation was also significant, $F(2, 30) = 5.33$, $p < .01$, $\eta_p^2 = .26$, but it showed a different pattern to that in Experiment 1. As can be seen in Figure 4, for simple objects, sensitivity increased from the mosaic through the global to the local interpretation (all *p*s $< .05$)—a near-identical pattern to that obtained in Experiment 1. For composite objects, by contrast, there were no significant differences among all three possible interpretations (all *p*s $> .5$).

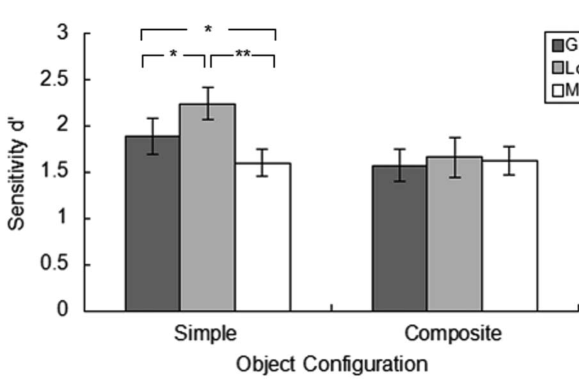


*Figure 4.* Mean change detection sensitivity, $d'$, as a function of the object configuration (simple, composite) in the memory display, separately for different interpretations (global, local, mosaic) in Experiment 2. Error bars denote 95% (within-subject) confidence intervals. Significant differences revealed by pairwise comparisons are indicated by asterisks. $^{*}$ $p < .05$, $^{**}$ $p < .001$.

Further analyses were conducted to compare the simple and composite object conditions in Experiments 1 and 2. First, an analysis of the simple objects revealed a main effect of interpretation, $F(2, 60) = 35.60$, $p < .0001$, $\eta_p^2 = .54$, with the highest sensitivity for local and the lowest sensitivity for mosaic figures (all *p*s $< .001$), without a significant difference between experiments ($p = .089$) and without a corresponding interaction ($p = .19$). This suggests that VWM for simple objects was overall comparable across the two experiments. Second, for the composite objects, there was a significant interaction between experiment and interpretation, $F(2, 60) = 3.58$, $p < .05$, $\eta_p^2 = .11$. In Experiment 1, there was a significant advantage for detecting a change for the global interpretation of composite objects, while no comparable effect was evident in Experiment 2. There were no differences in detecting the change for the local and mosaic interpretations in Experiments 1 and 2 (all *p*s $> .59$).

## Discussion

The results of Experiment 2 directly replicated the pattern of results for simple objects in Experiment 1, but revealed no evidence of object completion for composite figures. In fact, both global and local completion interpretations for composite objects yielded a level of performance that was the same (i.e., as low) as that for the mosaic baseline—suggesting that without the "priming" provided by the simple-object context, no particular grouping emerges. The combined results of Experiments 1 and 2 thus support previous findings showing that a given context can determine how composite objects are interpreted (see also Liu et al., 2006; Plomp et al., 2006; Plomp & Van Leeuwen, 2006; Rauschenberger et al., 2004). In fact, object representations in VWM may be constructed based on context-activated top-down knowledge. This knowledge frames how objects are represented, in turn determining processes of object recognition and the change/no-change decisions to be made in the present task (Bar, 2003; see also Conci & Müller, 2014). Thus, the actual completion representation derived from the visual input is constrained by the context within which an occluded object is presented.

# Experiment 3

The two experiments reported thus far demonstrate that, when presented within an appropriate context, objects are stored as (globally) completed representations in VWM, where the storage or maintenance of completed wholes draws on limited-capacity VWM resources. If this "resource" notion is correct, then varying the set size of the memory display such that it either stays within (two items) or exceeds (say four items) the available capacity for representing objects should have an influence on object completion in VWM. This idea was tested in Experiment 3.

## Method

Experiment 3 was basically identical to Experiment 1, with the following differences. Sixteen right-handed paid volunteers (eight female, eight male; mean age = 24.25 years; normal or corrected-to-normal vision) participated in the experiment. The memory display presented two possible set sizes: two or four objects. The stimulus set was based on five different shapes (adapted from Plomp & Van Leeuwen, 2006; Sekuler et al., 1994; Van Lier et al., 1995; see Experiment 1, Figure 1A–E) and consisted of composite and simple objects. As Experiment 1 had shown that global completion leads to superior VWM performance relative to local completion, in Experiment 3, only global completions were presented and compared to (baseline) mosaic interpretations. Thus, every simple figure could be one of two possible interpretations: global completion and mosaic (see Figure 1). A within-subjects design was used. The independent variables were set size (two, four), object configuration (simple, composite), interpretation (global, mosaic), and change (yes, no). The experiment was subdivided into two parts, with each part inducing one possible interpretation (global or mosaic interpretation), comparable with the procedure in Experiment 1. Participants were presented with the global and mosaic interpretation (experimental) parts in counterbalanced order (i.e., one half starting with the global and the other with the mosaic part). Within each part, different set sizes, object configurations, and change and no-change trials were presented in random order. There was one block with 16 practice trials and seven experimental blocks of 48 trials in each part, yielding 672 experimental trials in total.

### Results

Figure 5 displays the sensitivity $d'$ as a function of set size, separately for different object configurations and interpretations. A repeated-measures ANOVA with main terms for set size, object configuration, and interpretation revealed the main effects of set size, $F(1, 15) = 506.11$, $p < .0001$, $\eta_p^2 = .97$, object configuration, $F(1, 15) = 13.78$, $p < .01$, $\eta_p^2 = .48$, and interpretation, $F(1, 15) = 27.75$, $p < .0001$, $\eta_p^2 = .65$, to be significant. Sensitivity was higher for set size 2 ($d' = 2.79$) than for set size 4 ($d' = 1.25$), higher for simple ($d' = 2.12$) than for composite ($d' = 1.91$) objects, and higher for global completion ($d' = 2.17$) than for mosaic interpretations ($d' = 1.86$). Most importantly, the interaction between set size and interpretation was significant, $F(1, 15) = 12.65$, $p < .01$, $\eta_p^2 = .46$: as the set size increased from two to four objects, the difference between global completion and mosaic interpretations decreased (mean difference: .49, $p < .0001$, and .14, $p < .05$, for set sizes two and four, respectively).

### Discussion

Experiment 3 was performed to examine how object completion in VWM is affected by memory capacity, as tested by means of a set size manipulation. The results replicated the findings from Experiment 1, with higher performance for the global completion than for the mosaic interpretation for both simple and composite objects. Note that completion also interacted with set size: the benefit for global (relative to mosaic) configurations largely decreased when set size increased from two to four items. This pattern is consistent with the idea that, with an increase in the number of to-be-memorized objects, there is an increase in storage demands; as a result, less processing resources are available for each individual object, leading to a decline of change detection performance overall. However, in addition to this overall decline, the performance difference between global and mosaic configurations is reduced, which may be taken to indicate that completion occurs only when sufficient mnemonic resources are available.

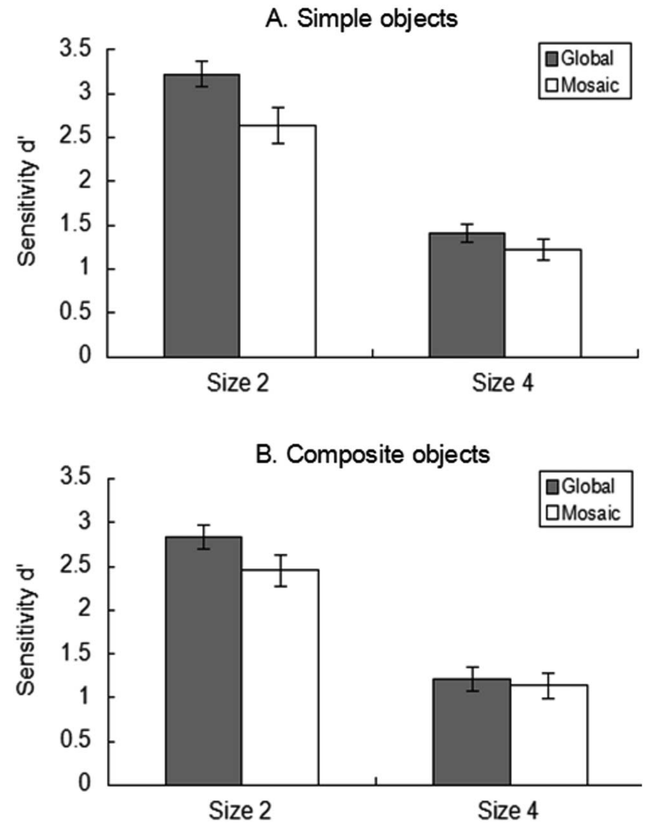


*Figure 5.* Mean change detection sensitivity, $d'$, as a function of memory display set size, separately for different interpretations (global, mosaic) and object configurations (A. simple objects; B. composite objects) in Experiment 3. Error bars denote 95% (within-subject) confidence intervals.

## General Discussion

The present study investigated VWM for composite objects using a change detection paradigm and measuring performance in terms of (change detection) sensitivity $d'$, that is, how well a participant was able to distinguish between trials on which the probe changed as compared with staying the same. The results from three experiments consistently showed that participants performed overall better with simple than with composite objects. Moreover, Experiment 1 revealed better performance for global completion as compared with local completion and mosaic interpretations. This global completion advantage was obtained only when the simple-object context supported a global object interpretation of the amodal stimuli. By contrast, without an appropriate context (in Experiment 2), no such benefit for global completions was found. Experiment 3 further showed that, even with an appropriate context, the difference between global completion and mosaic interpretations reduced as the memory display set size increased to (or beyond) the maximum of VWM capacity.

Taken together, these results indicate that amodal completion occurs for objects represented in VWM and this completion process is significantly affected by the context of simple objects (presented together with the amodal stimuli): Completion occurs only when the context supports a given interpretation of the completed object. Without corresponding context, change detection for the various kinds of composite objects is comparable, with sensitivity measures for global (and local) completion types being similar to VWM performance with mosaic configurations. Previous studies have already shown that context affects how a given composite object is perceived (Liu et al., 2006; Plomp et al., 2006; Plomp & Van Leeuwen, 2006; Rauschenberger et al., 2004). While our results are in line with these findings, they extend them by showing that the influence of context on processes of amodal completion continues from basic perceptual analysis to subsequent stages related to the short-term retention of the presented stimuli in VWM. This influence of object completion on VWM may be due to a top-down facilitation mechanism as demonstrated by Bar (2003). On this view, recognition of a visual image would activate concurrent expectations about likely interpretations associated with the specific image. Via such top-down expectancies, contextual knowledge or prior expectations might influence the interpretation of an object in VWM (see also Conci & Müller, 2014). Thus, for our paradigm, a consistent context would activate a specific interpretation of a given composite object, consequently biasing the completion type that determines a given VWM representation.

Our results reveal that composite objects tend to be represented as globally completed wholes in VWM, suggesting that memory-related processing is determined preferentially by global object structure—in line with several previous studies that found global (but not local) completion was the dominant interpretation of an occluded object (De Wit & Van Lier, 2002; Sekuler, 1994; Sekuler et al., 1994; Van Lier, 1999, 2001; Van Lier & Wagemans, 1999). There is some evidence suggesting that initial stimulus processing may represent occluded objects in terms of a mosaic interpretation (e.g., in a visual search task, see Plomp et al., 2006; Rauschenberger & Yantis, 2001). However, as processing time increases, this interpretation is superseded by complete-object representations (Plomp et al., 2006; Plomp & Van Leeuwen, 2006).

A second influence on completion processes in memory is the limited capacity of VWM itself. Experiments 1 and 3 used comparable experimental manipulations, presenting a consistent stimulus context to facilitate (global) completion. In Experiment 1, detection of the change was somewhat more difficult for globally completed composite as compared with simple objects. By contrast, performance with mosaic configurations was comparable for composite and simple objects (while being overall reduced relative to performance for composite and simple global objects). This pattern of results indicates that the storage of a completed whole requires additional mnemonic resources, over and above those required for the representation of the very same unoccluded object. That is, the demands associated with completion directly impact memory capacity: A complete-object representation in VWM affects storage in that it occupies more capacity. This is consistent with previous visual search studies showing that search efficiency is reduced for complete-object representations relative to comparable uncompleted objects (Davis & Driver, 1998; He & Nakayama, 1992; Rensink & Enns, 1998).

On the other hand, although the composite objects were more likely to be represented in VWM as completed wholes compared with other interpretations, when there was a concurrent increase in storage demands (i.e., when the memory display set size increased in Experiment 3), the advantage for the global completion condition greatly reduced. As suggested by Alvarez and Cavanagh (2004), the number of items stored in VWM depends on the visual information load of the individual items. Processing of completed objects presumably poses higher demands on the available (limited) resources. When the number of the composite objects exceeds the available VWM capacity, it appears that completed objects are simply represented in terms of their corresponding visible fragments (i.e., in terms of a mosaic interpretation), thus consuming fewer resources.

In this view, the maintenance of the completed wholes is not only, or simply, influenced by the number of objects, but also limited by completion processes, which requires resources. This is in line with Alvarez and Cavanagh's (2008) suggestion that VWM may involve two dissociable stages: In the first stage, low-resolution "boundary features" are extracted by means of parallel perceptual processing, whereas in the second stage, more detailed, high-resolution features are extracted via serial, attentive perceptual processing. Thus, different representations of the same composite stimuli stored in VWM may be extracted at different stages of perceptual processing. Once the completed representations are available, they are represented preferentially as global wholes compared to other interpretations—at least as long as enough resources are available.

## Implications for Limitation of VWM Capacity

In the present study, VWM capacity for simple or composite objects was limited to about two items, as indicated by estimations of the capacity estimate *K* (see Table 2). Thus, compared with Luck and Vogel (1997), who report a *K* value of about four objects, our rather complex shape stimuli yielded a relatively low capacity estimate. Nevertheless, our estimates are in accordance with other studies that presented relatively complex items, such as Snodgrass line drawings or random polygons (see Alvarez & Cavanagh, 2004). According to our current results, completion resulted in reduced change detection performance and was more likely to be compromised as the number of stored items increased. This presumably indicates that VWM can represent visual information until some maximum is reached, but the number of items represented is crucially determined by completion and complexity. This is consistent with the notion of VWM as a system with a storage capacity that varies as a function of object complexity (Alvarez & Cavanagh, 2004; Xu, 2002). Interpreted within this perspective, our results would indicate that the encoding of items into VWM draws on a more continuous resource, instead of involving an all-or-none (e.g., slot-like) storage process, arguing against the view that VWM represents a fixed number of items

Table 2
*Capacity Estimates K*

| Experiment | Set size | Simple | Composite |
|---|---|---|---|
| 1 | 3 | 2.06 | 1.79 |
| 2 | 3 | 1.87 | 1.62 |
| 3 | 2 | 1.63 | 1.56 |
| | 4 | 1.83 | 1.65 |

regardless of complexity (Awh et al., 2007; Luck & Vogel, 1997; Rouder et al., 2008).

Previous formal models of change detection to estimate VWM capacity assume that observers encode only a simple memory representation that includes no higher-order information (e.g., Luck & Vogel, 1997; Zhang & Luck, 2008). However, real-world scenes are typically complex and present structure that provides higher-order constraints on to-be-remembered items (for a review, see Brady, Konkle, & Alvarez, 2011; Brady & Tenenbaum, 2013; Conci & Müller, 2014). Our study supports the view that contextual information and prior knowledge are utilized to perform working memory tasks. The same composite objects were represented differently depending on the contextual information, and each representation requires varying amounts of mnemonic resources. Moreover, while existing formal models of VWM treat all items independently of each other (e.g., Luck & Vogel, 1997; Zhang & Luck, 2008), the present findings suggest that VWM encodes grouped items. In light of the current results, approaches taking higher-order (context) information and relational structures between items into consideration might be better suited to account for human change detection performance.

## Conclusion

Previous studies have shown that completed objects are processed rather efficiently, in sequential perceptual (mosaic and completion) stages. Our findings indicate that at a later, postperceptual stage, the maintenance of composite object representations in VWM is influenced by contextual information and VWM capacity limits. Composite objects are preferentially stored as globally completed wholes when primed by concurrent simple global objects, but completion only occurs with sufficient available mnemonic resources. These findings support the view of VWM as reflecting a continuous resource, where capacity limitations depend on the structured representation of to-be-remembered objects.

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## 2.4 Study 4: Object maintenance beyond their visible parts in working memory

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Contributions:

The author of this dissertation designed and programmed the experiment, collected and analyzed data, created plots, interpreted the results and wrote the manuscript.

Thomas Töllner helped with the data analysis and with interpreting the results, and he commented on the manuscript.

Hermann Müller helped with the interpretation of the results, and he commented on and helped revising the manuscript.

Markus Conci conceived and supervised the project, participated in designing the experiments and interpreting the results, and he commented on and helped revising the manuscript.

# Object maintenance beyond their visible parts in working memory

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## Abstract

Completion of a partially occluded object requires that a representation of the whole is constructed based on the information provided by the physically specified parts of the stimulus. Such processes of amodal completion rely on the generation and maintenance of a mental image that renders the completed object in visual working memory (VWM). The present study examined this relationship between VWM storage and processes of object completion. We recorded event-related potentials to track VWM maintenance by means of the contralateral delay activity (CDA) during a change detection task in which to-be-memorized composite objects (notched shapes abutting an occluding shape) were primed to induce either a globally completed object or a non-completed, mosaic representation. The results revealed an effect of completion in VWM despite physically identical visual input: Change detection was more accurate for completed as compared to mosaic representations when observers were required to memorize two objects, and these differences were reduced with four memorized items. At the electrophysiological level, globally completed (versus mosaic) objects gave rise to a corresponding increase in CDA amplitudes. These results indicate that, while incorporating the occluded portions of the presented shapes requires mnemonic resources, the complete-object representations thus formed in VWM improve change detection performance by providing a more simple, regular shape. Overall, these findings demonstrate that mechanisms of object completion modulate VWM, with the memory load being determined by the structured representations of the memorized stimuli.

## Introduction

Amodal completion refers to the phenomenon that occluded parts of an object are perceptually ‘filled in’ (Michotte, Thines, & Crabbe, 1964/1991), that is, missing information is (re-) constructed based on the partial physical stimulation available (see Figure 1, composite, for example stimuli). Representing amodally completed objects has been suggested to rely on mental imagery (Nanay, 2010). While completion is largely dependent on the structural properties of a given stimulus (Van Lier, Van der Helm, & Leeuwenberg, 1994), it may additionally be influenced by background information, such as semantic knowledge about a given object or the context within which it is presented – providing further information about what the occluded parts of an object (may) look like (Hazenberg & Van Lier, 2016; Rauschenberger, Peterson, Mosca, & Bruno, 2004). Construction of a mental image typically engages visual working memory (VWM) resources (Baddeley & Andrade, 2000). On this view, rather than just subserving passive maintenance of visual information for short periods of time, VWM does also involve active processes of generating (hidden) parts of objects in memory. The current study was designed to investigate such active object completion processes in VWM, that is, to elucidate how physically specified parts of a stimulus are combined with completed fragments to generate a coherent, whole-object representation.

A common and widely used paradigm for studying VWM is change detection (Luck & Vogel, 1997). In this paradigm, participants are asked to remember a set of objects in an initial memory display. After a retention interval, a test display is presented and participants have to indicate whether a change has occurred in one of the objects in the test as compared to the memory array. The typical finding is that some three to four objects can be maintained concurrently in VWM (Luck & Vogel, 1997; Cowan, 2001). However, the number of items that can be stored has also been shown to be influenced by the information load associated with the individual, to-be-memorized objects. For instance, Alvarez and Cavanagh (2004) demonstrated that change detection performance varies as a function of stimulus complexity, with a reduced number of only about one memorized item for more complex objects (e.g., Chinese characters, shaded cubes), as compared to four items for more simple objects (e.g., colored squares). Thus, VWM is limited in capacity: it can represent only relatively few items, where the overall number of items that can be retained varies for different types of objects.

Studies that examined participants' electroencephalogram (EEG) in change detection tasks showed that an event-related difference wave manifesting during the delay period (between the memory and test displays) over lateral posterior parietal and occipital electrode sites – referred to as 'contralateral delay activity' (CDA) – can serve as an online marker of current VWM load: the CDA amplitude increases with the number of items (to be) held in memory, until reaching an asymptotic limit indicative of an individual's memory capacity (Vogel & Machizawa, 2004). Given that the CDA (which is obtained in the delay period) reflects processes of maintenance (independent of later processes involved in the comparison of the memorized items with the test probe; see Awh, Barton, & Vogel, 2007), it can be used to directly examine how stimuli are represented in VWM. For instance, with relatively few to-be-memorized items, CDA amplitudes were found to be larger for more complex (random polygons) than for simple objects (colored squares) – in line with the view that VWM is modulated by stimulus attributes and the load they place on processes of maintenance (Luria, Sessa, Gotler, Jolicœur, & Dell'Acqua, 2010; Gao et al., 2009; Töllner, Conci, Rusch, & Müller, 2013). Moreover, larger CDA amplitudes were observed for identical stimuli when the task required the encoding of objects with high precision (Machizawa, Goh, & Driver, 2012). This demonstrates that identical visual input may change the memory load depending on top-down demands (see also Balaban & Luria, 2016). Nevertheless, it remains an open issue whether the CDA varies with the extent to which processes of completion modify a given object in VWM.

The question at issue here, namely: the role of object completion in VWM, was recently examined in a behavioral study employing the change detection paradigm (Chen, Müller, & Conci, 2016). Chen et al. presented memory displays that were physically identical, but varied the structural information of the objects' representations in memory by introducing additional, contextual information. The memory displays participants were presented with were essentially comparable to the example displays depicted in Figure 2 (except that, in Chen et al., 2016, participants were not pre-cued to the task-relevant side of the display by an arrow symbol). A given memory display consisted either of composite objects (i.e., presenting a notched figure adjacent to a square) or of simple objects (i.e., comparable shapes but without the adjacent square). Importantly, the simple object could be one of several possible interpretations of the notched figure, with a global, symmetrical shape that provides a completed interpretation of the composite object (Figure 1, global), or a so-called 'mosaic' figure (Figure 1, mosaic), where mosaic simply refers to a 2-D cut-out outline shape identical to the visible part of the figure (Sekuler & Palmer, 1992). Presentation of the memory display was followed by a brief delay, after which a (simple-object) test probe appeared. The task was to decide whether this probe was the same as or different from the corresponding item in the memory display. Each block of trials presented only one type of (simple) objects (either global or mosaic figures), to enforce, or 'prime', a consistent interpretation of the composite objects within the given block. The results revealed global objects to yield higher change detection accuracy, indicative of an advantage in retaining completed wholes over partial shapes (Chen et al., 2016, Experiment 1). This advantage for completed, relative to mosaic, *composite* objects disappeared when global and mosaic *simple* object displays were presented randomly intermixed within trial blocks (Chen et al., 2016, Experiment 2), indicating that the effect of completion is determined by some top-down set provided by a consistent context of the available simple object interpretations.

Importantly, Chen et al. (2016) compared change detection accuracy for physically identical composite objects that participants were made to interpret either as completed wholes or as non-completed mosaic objects. Consequently, rather than being attributable to an influence of perceptual shape discriminability, the performance advantage for global (relative to mosaic) composite objects obtained by Chen et al. (2016, Experiment 1) can only be attributed to the additional completion process, which renders binding of the physical parts of the object with the occluding parts of the surface. If VWM load is indeed modulated by the completion of the memorized objects, this would predict that the alternative representations of the composite object would manifest in a modulation of the CDA amplitude. On this view, the CDA amplitude not only reflects the passive retention of items, but also the resource demands associated with processes required for integrating fragments into a coherent, whole-object representation. This viewpoint contrasts with a more passive conception of VWM, where the CDA would only be related to the basic storage of individuated items without any concurrent processing of the retained stimulus material.

The present study was designed to decide between these two alternative views and to extend our previous, purely behavioral findings regarding the relationship between VWM storage and the completion of objects (Chen et al., 2016). To this end, we combined behavioral measures with analysis of the CDA as an electrophysiological marker of VWM load. Event-related potentials (ERPs) were recorded from young adults while they performed a change detection task. On each trial (Figure 2), observers were first presented with an arrow cue indicating the relevant, to-be-memorized half of the display. Next, a brief bilateral array presented composite or simple objects (either global or mosaic shape interpretations; see Figure 1) for 300 ms. The (300-ms) presentation time of the memory display was set in accordance with previous studies (Sekuler & Palmer, 1992; Rauschenberger et al., 2004; Chen et al., 2016; Gerbino & Salmaso, 1987), which showed that completion only occurs when a given partially occluded stimulus is presented for at least 100–200 ms. Moreover, we provided a consistent context of simple-object trials within a given block, so as to effectively enforce a given interpretation of the partially occluded objects (Rauschenberger et al., 2004; Chen et al., 2016). Participants' task was to remember the items in the cued hemifield and indicate, after a brief delay, whether a subsequently presented test display did or did not contain a changed object. If completion modulates VWM load, the identical composite objects should yield a difference in performance for globally completed versus mosaic interpretations.

**Method**

***Participants.*** Seventeen right-handed volunteers (8 males), with normal or corrected-to-normal vision ($M$ = 24.22 years, $SD$ = 2.90 years), took part in this study for payment of € 8.00 per hour. All participants provided written informed consent. The experimental procedures were approved by the local ethics committee (Department of Psychology, Ludwig-Maximilians-Universität München). Sample size was determined on the basis of previous, comparable studies (e.g., Luria et al., 2010), aiming for 85% power to detect an effect size of 0.8 with an alpha level of .05.

***Apparatus and Stimuli.*** Stimuli were black line drawings (0.2 cd/m$^2$) presented against a light gray background (178 cd/m$^2$) on a 19-inch computer monitor (1024×768 pixel screen resolution, 85-Hz refresh rate). The stimulus set was based on six different shapes (adapted from Van Lier et al., 1995; Plomp & van Leeuwen, 2006; Sekuler, Palmer, & Flynn, 1994; see Figure 1). The composite figure included a square with a second shape positioned partly occluded next to the square (Figure 1, Composite). The simple figure was presented in two possible alternative interpretations of the composite object: global and mosaic (Figure 1, Simple-Global, Simple-Mosaic). Global figures presented a globally completed, symmetrical shape, whereas a mosaic figure simply presented a 2-D cutout outline shape identical to the visible part of the partly occluded figure. At a viewing distance of 60 cm, each simple figure touched a circular region with a radius of 0.6° of visual angle. The square of the occluded objects subtended 1.1° x 1.1°. For each memory display, four or eight distinct objects of the same completion type were presented randomly at ten positions within a circular region with a radius of 5.0°, with two or four objects in each hemifield. A given shape could appear only twice at most in the same display. The test probe was identical to the item in the same position of the memory display in half the trials and different in the other half. It should be noted that ”same” or “different” in this experiment refers to object identity, rather than to the completion type. For example, the occluded cross in Figure 1a (Composite) would be considered the same object as the other two variants of simple objects presenting a cross-shaped item (Figure 1a, Simple).

***Procedure and Design.*** Each trial started with the presentation of a central fixation cross for 500 ms, followed by an arrow cue pointing to either the left or the right for 500 ms. Next, participants were presented with a memory display of either simple or composite objects for 300 ms. Following a blank screen of 900 ms, the test display was presented until a response was issued. Participants were instructed to memorize the stimuli presented in the hemifield indicated by the arrow cue and respond with left and right mouse keys to indicate whether the test probe in the cued hemifield was the same as or different from the corresponding item in the memory display. Left/right responses were counterbalanced across observers to control for stimulus-response compatibility effects. Observers were asked to respond as accurately as possible, without stress on response speed. Trials were separated from each other by a random interval between 300 and 400 ms. Figure 2 illustrates typical examples of a trial sequence.

There were eight experimental blocks, with 160 trials each. Each block presented only one type of possible interpretations (global or mosaic) to consistently enforce the respective interpretation of the composite objects within a given experimental block (Chen et al., 2016). The eight blocks were presented in random order. Within each block, the different configurations (simple, composite) and change/no-change trials were presented in randomized order across trials. All participants performed eight practice blocks of 40 trials each on the day before the experiment, to become familiar with the task.

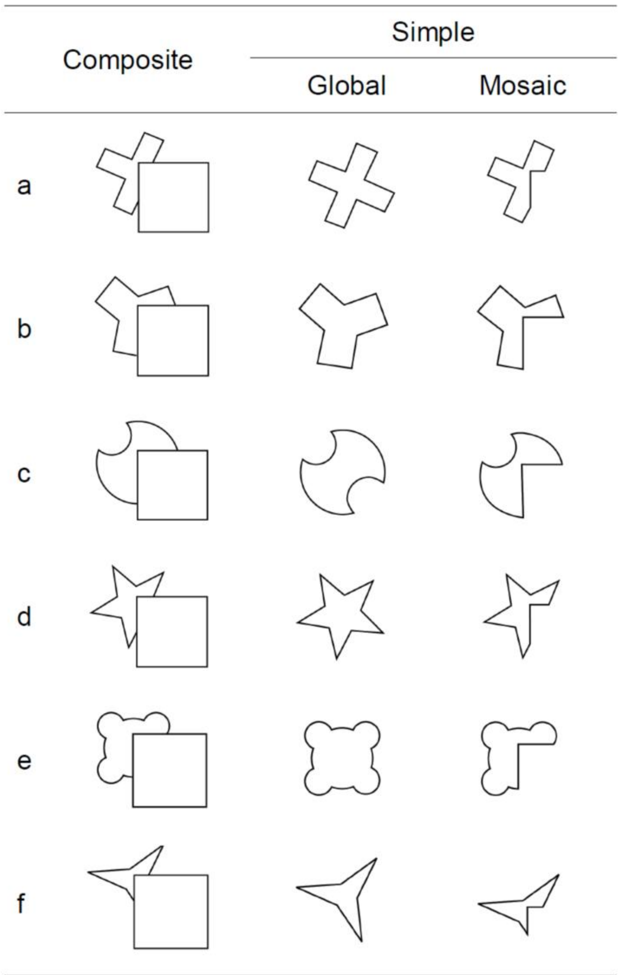


**Figure 1.** Illustration of the experimental stimuli with their respective composite and simple versions (global and mosaic interpretations).

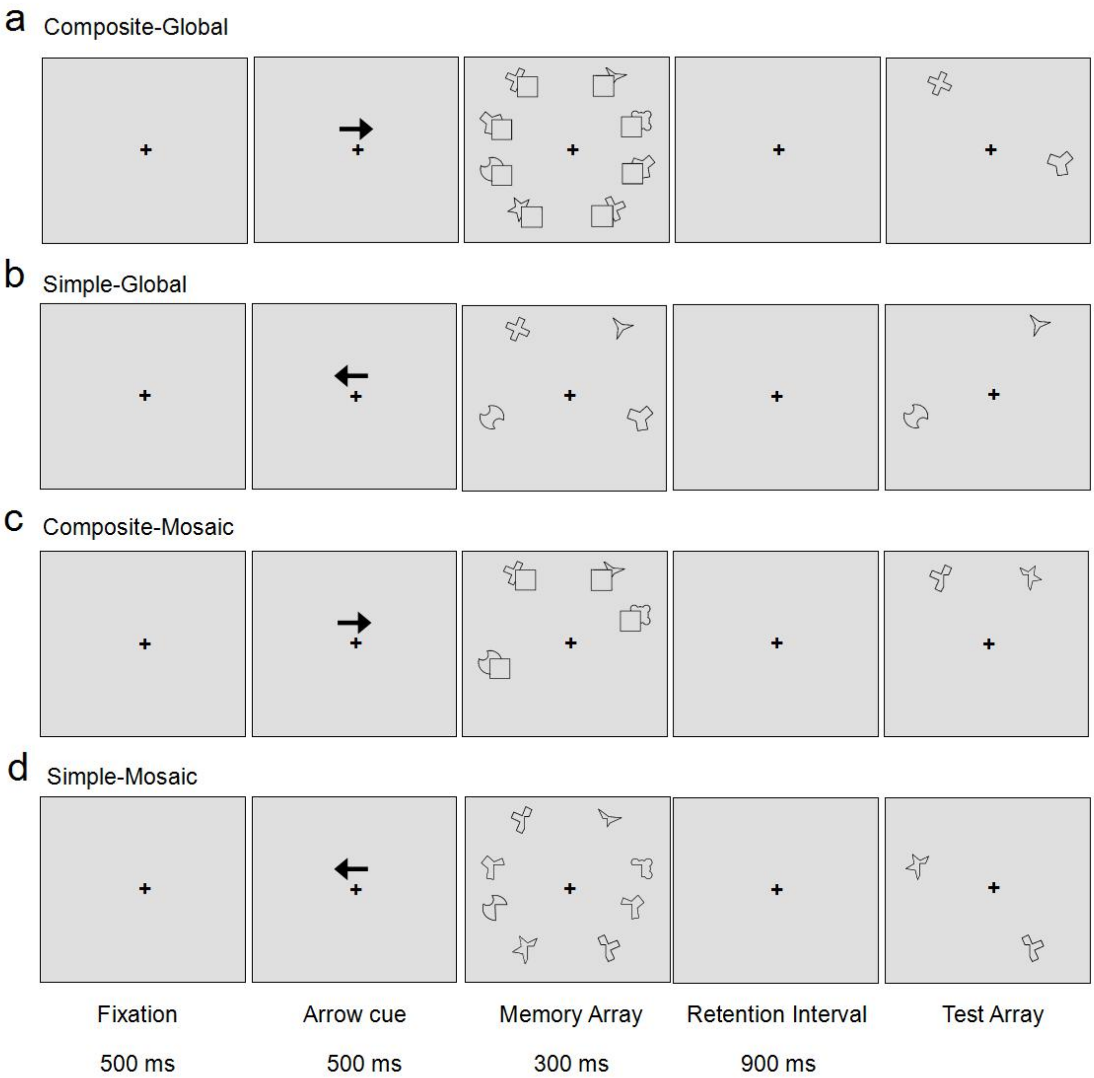


**Figure 2.** Trial sequence. Example trial (a) shows a set size 4, composite-object memory display followed by a test display supporting a global interpretation. Participants were instructed to memorize only the stimuli presented on the side indicated by the arrow prior to the memory display. The correct response would be 'same'. Example trial (b) presents a set size 2, simple-object memory display, with global (i.e., symmetric) shapes (correct response: "same"). Note that the example trials in (a) and (b) were presented in the same block (in randomized order), to coherently support a 'global' interpretation of the occluded objects. Example trials (c) and (d) show a composite- and a simple-object memory display with two and four objects, respectively. Displays as depicted in (c) and (d) engender a 'mosaic' interpretation, and were also presented within the same block (correct responses: 'different').

***EEG Recording and Data Analysis.*** The EEG was continuously recorded using 64 Ag/AgCl active electrodes (Brain Products Munich) according to the international 10-10 System with a sampling rate of 1000 Hz. Vertical and horizontal eye movements were monitored with electrodes placed at the outer canthi of the eyes, and respectively, the superior and inferior orbits. The electrode signals were amplified using BrainAmp amplifiers (BrainProducts, Munich) with a 0.1 – 250-Hz bandpass filter. All electrode impedances were kept below 5 kΩ. During data acquisition, all electrodes were referenced to FCz, and re-referenced off-line to averaged mastoids. Prior to segmenting the EEG, the raw data was visually inspected in order to manually remove nonstereotypical noise. Next, an infomax-independent component analysis was run to identify components representing blinks and horizontal eye movements, and to remove these artifacts before backprojection of the residual components. Subsequently, the data were band-pass filtered using a 0.1 – 40-Hz Butterworth IIR filter (24 dB/Oct). Signals were then averaged off-line over a 1200-ms epoch relative to a 200-ms pre-stimulus (memory display) baseline. Trials with artifacts –defined as any signal exceeding ± 60 $\mu$V, bursts of electromyographic activity (as defined by voltage steps/sampling point larger than 50 $\mu$V) and activity lower than 0.5 $\mu$V within intervals of 500 ms (indicating bad channels) – were excluded from averaging. The contralateral delay activity (CDA) was measured at parieto-occipital electrodes (PO7/8) as the difference in mean amplitude between the ipsilateral and contralateral waveforms relative to the memorized display, with a measurement window of 500–1200 ms after the onset of the memory display. Trials with incorrect behavioral responses were discarded from the ERP analyses.

Differences in behavioral accuracy and neural measures (CDA amplitudes) were examined for composite objects by performing two-way repeated-measures analyses of variance (ANOVAs) with the factors set size (two, four) and interpretation (global, mosaic). Note that the focus of the analysis on the maintenance of identical composite objects with varying interpretations (global vs. mosaic) controls for the influence of differential (perceptual) feature discriminability between the memory displays. Thus, any difference in the CDA components between global and mosaic representations can only be due to their differential maintenance demands, rather than to perceptual dissimilarity or memory–test comparisons. In addition to this main analysis of composite objects, we performed analogous analyses for simple objects.

## Results

### *Composite Objects*

Behavioral Data. Figure 3a depicts the mean percentage of correct responses for composite objects as a function of set size, separately for the different interpretations. A repeated-measures ANOVA on the accuracy data was performed with the factors set size and interpretation, yielding main effects of set size, $F(1, 16) = 767.07$, $p < .0001$, $\eta_p^2 = .980$, and interpretation, $F(1, 16) = 39.06$, $p < .0001$, $\eta_p^2 = .709$. Accuracy was higher for set size 2 (84%) than for set size 4 (67%), and higher for global (77%) than for mosaic interpretations (74%). The interaction between set size and interpretation was also significant, $F(1, 16) = 11.62$, $p = .004$, $\eta_p^2 = .421$: a significant difference between global (86%) and mosaic interpretations (81%) manifested with set size 2, $t(16) = 6.66$, $p < .0001$, while this difference was reduced for set size 4 (global: 68%; mosaic: 67%), $t(16) = 1.88$, $p = .078$. Replicating our previous findings (Chen et al., 2016), this reduction in performance can be attributed to the reduced scanning time available per object with an increased set size. As a result, not all objects are effectively completed for the larger, 4-item display. With larger memory arrays, there would then also be a higher chance of guessing, as attention is less likely focused on the object that is tested later on – so that this item might not have been encoded with sufficient detail. Moreover, accuracy might also be compromised by errors arising from the comparison of an item held in memory with the test probe presented (Awh et al., 2007), and these comparison errors might also increase with set size.

In a next step, we computed Cowan's *K* (Cowan, 2001), an estimate of visual memory capacity, which allows correcting for errors that result from memory storage failures. Note, however, that K does not take care of errors arising from the comparison process – which is why K might somewhat underestimate the number of items stored (though this underestimation should be comparable for global and mosaic interpretations). Essentially, this correction assumes that if an observer can hold *K* items in memory from an array of *S* items, the item that changed should be one of the items being held in memory on *K/S* trials, resulting in correct performance on *K/S* of the trials on which an item changed. *K* is computed according to the formula: (Proportion Hits – Proportion False Alarms) × Set Size, where the perceptual sensitivity (the difference between hits and false alarm) is multiplied by set size to take into account the number of to-be-memorized items. The capacity *K* estimated in this way revealed that effectively only 1–2 composite objects could be remembered (see Figure 3b). A repeated-measures ANOVA of the *K* estimates yielded a main effect of interpretation, $F(1, 16) = 23.36$, $p < .0001$, $\eta_p^2 = .593$: significantly more items were maintained with global ($K = 1.45$) as compared to mosaic ($K = 1.28$) representations. No other significant effects were obtained, *ps* > .25.

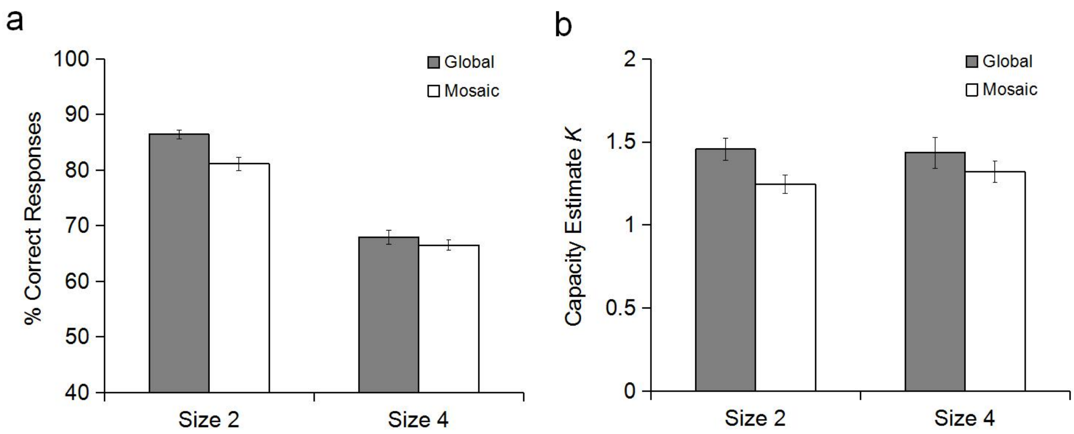


**Figure 3.** Mean percentage of correct responses (a) and capacity estimate *K* (b) as a function of memory set size for the different interpretations (global, mosaic) of the composite objects. Error bars indicate 95% (within-participant) confidence intervals.

ERP Data. The corresponding ERP waves for composite objects are plotted in Figure 4a. An ANOVA on the mean CDA amplitudes with the factors set size and interpretation revealed a main effect of interpretation, $F(1, 16) = 6.12$, $p = .025$, $\eta_p^2 = .277$. As depicted in Figure 4b, the mean CDA amplitude was larger for the global (-1.22 $\mu$V) as compared to the mosaic interpretation (-.88 $\mu$V). No other significant effects were obtained (*p*s > .25). This finding mirrors the pattern of the capacity estimate *K* (Figure 3b), demonstrating an effect of interpretation on the amplitude of the CDA.

The individual differences in the CDA amplitude between global and mosaic interpretations also correlated with the corresponding differences in accuracy (with values averaged across set sizes): $r = –.66$ (95% CI [-.84, -.42]), $p = .004$ (Figure 4c). The statistical significance of the correlation coefficient was determined by comparing the observed correlations with results derived from 10000 permutations of the two variables (i.e., the difference in accuracy and the difference in the CDA amplitude between global and mosaic interpretations). This ensures that the significant correlation is not attributable to any outliers in the data.

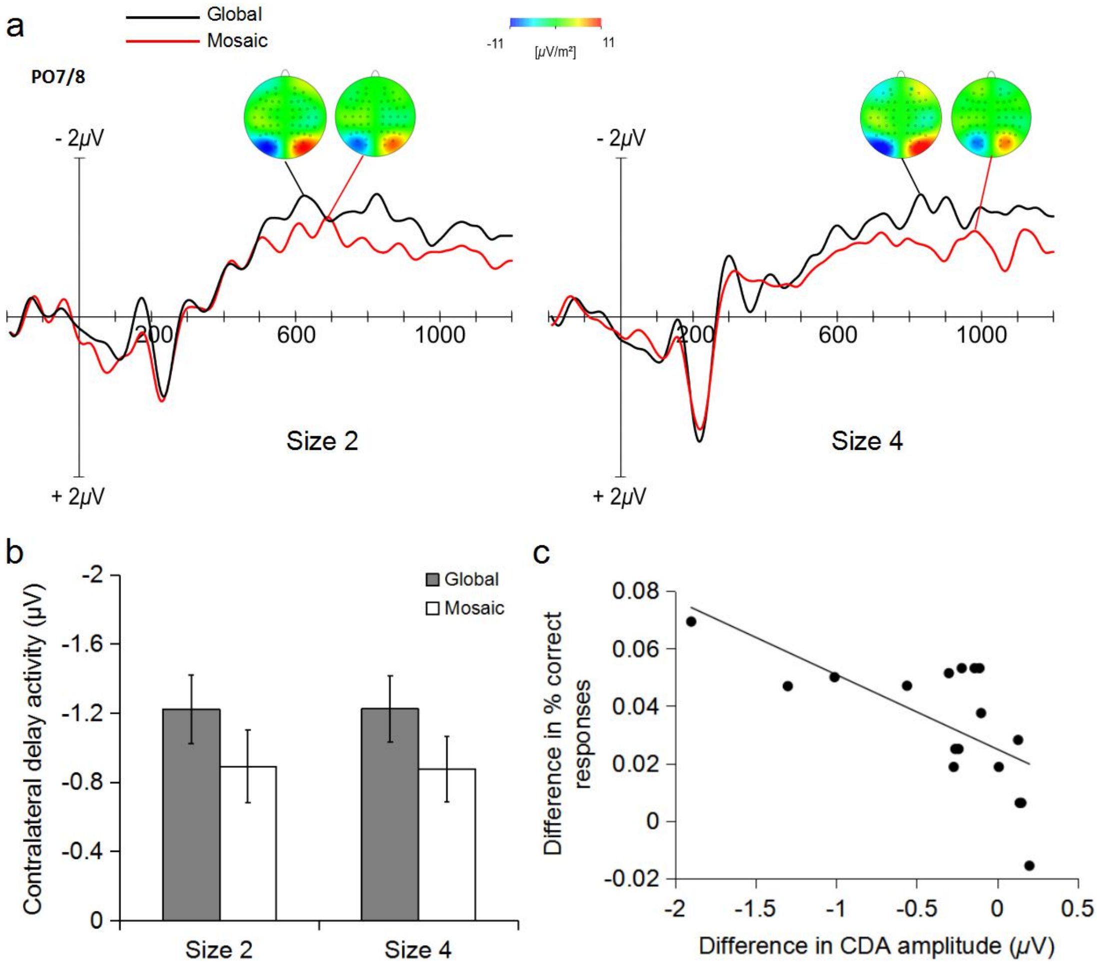


**Figure 4.** ERP results for composite objects. Panel (a) depicts the grand average ERP waveforms (contralateral minus ipsilateral activity relative to the memorized display hemifield) time-locked to the onset of the memory display at electrodes PO7/8, in the composite-object condition for Set Size 2 (left panel) and Set Size 4 (right panel). Scalp distribution maps depict the point in time at which the respective difference waves reached their maximum. For illustration purposes, the grand average waveforms shown here were low-pass-filtered at 12 Hz (24 dB/Oct). The graph in (b) shows the mean CDA amplitudes in the time window of 500–1200 ms after the onset of the memory display at electrodes PO7/8 as a function of memory set size, separately for the different interpretations (global, mosaic). Error bars indicate 95% (within-participant) confidence intervals. Panel (c) illustrates the correlation between the difference in CDA amplitudes and the corresponding difference in accuracy between global and mosaic interpretations (averaged across set sizes).

## Simple Objects

Behavioral Data. Figure 5 displays the mean percentage of correct responses (a) and the corresponding capacity estimates *K* (b) for simple objects as a function of set size, separately for the different interpretations. A repeated-measures ANOVA on the accuracy data with the factor set size and interpretation yielded main effects of set size, $F(1, 16) = 479.30$, $p < .0001$, $\eta_p^2 = .968$, and interpretation, $F(1, 16) = 42.34$, $p < .0001$, $\eta_p^2 = .726$. Accuracy was higher for set size 2 (88%) than for set size 4 (70%), and higher for global (82%) than for mosaic interpretations (77%). The interaction was non-significant, $p > .25$. Moreover, calculation of the capacity estimates *K* (as in the analysis above) again revealed that only 1–2 simple objects could be remembered (see Figure 5b). A repeated-measures ANOVA on the *K* estimates revealed a main effect of interpretation, $F(1, 16) = 26.71$, $p < .0001$, $\eta_p^2 = .625$, with higher capacity for global ($K = 1.73$) than for mosaic interpretations ($K = 1.43$). No other significant effects were obtained, all *ps* > .25.

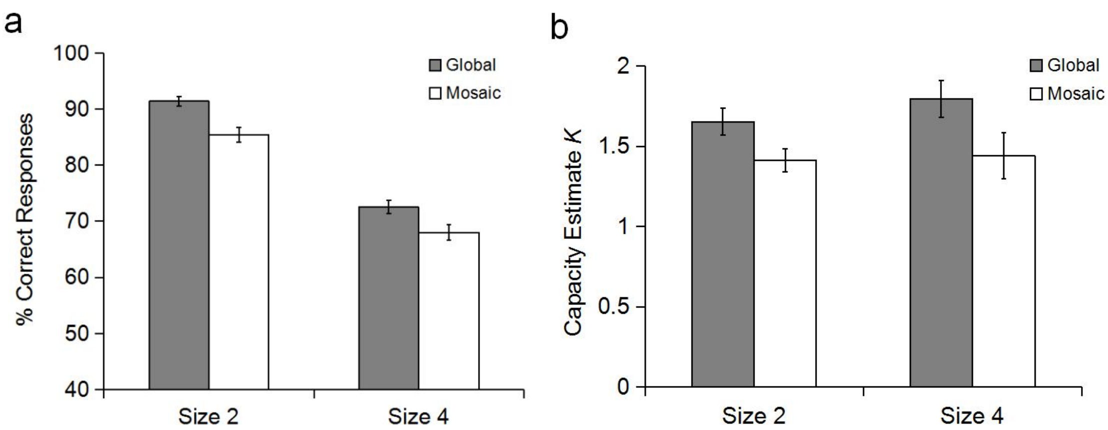


**Figure 5.** Mean percentage of correct responses (a) and capacity estimate *K* (b) as a function of memory set size for the different interpretations (global, mosaic) of the simple objects. Error bars denote 95% (within-participant) confidence intervals.

ERP Data. The corresponding ERP waves for the simple objects in the global and mosaic conditions are plotted in Figure 6. An ANOVA on the mean amplitudes of the CDA with the factors set size and interpretation revealed a main effect of interpretation, $F(1, 16) = 4.77$, $p = .044$, $\eta_p^2 = .230$: of note, the mean CDA amplitude was larger for the mosaic shapes (-1.24 $\mu$V) than for the global shapes (-1.00 $\mu$V); recall that the reverse pattern was found with composite objects. No other significant effects were obtained (set size, $F(1, 16) = 1.67$, $p = .21$, $\eta_p^2 = .095$; interaction, $F(1, 16) = 1.25$, $p = .28$, $\eta_p^2 = .073$).

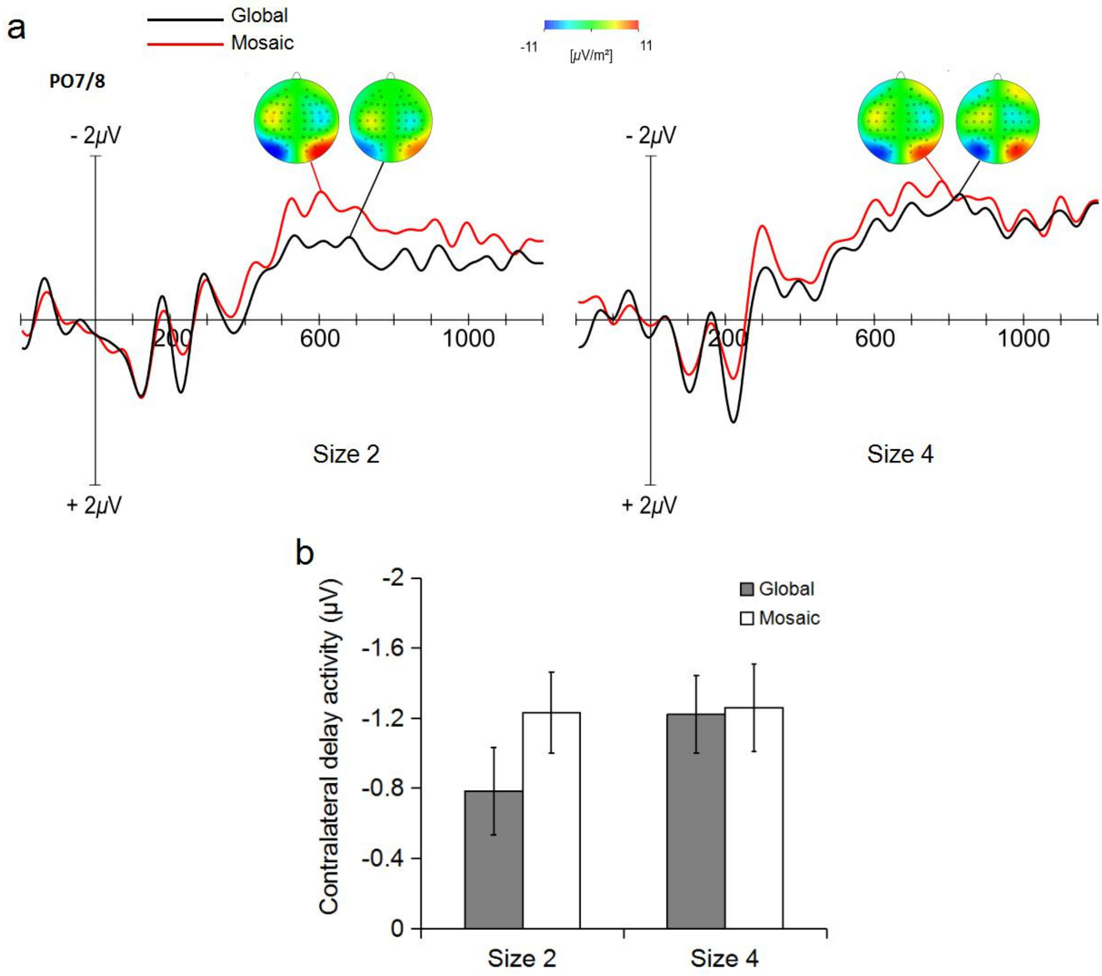


**Figure 6.** ERP results for simple objects. Panel (a) depicts the grand average ERP waveforms (contralateral minus ipsilateral activity relative to the memorized display hemifield) time-locked to the onset of the memory display at electrodes PO7/8, in the simple-object condition for Set Size 2 (left panel) and Set Size 4 (right panel). Scalp distribution maps depict the point in time at which the respective difference waves reached their maximum. For illustration purposes, the grand average waveforms shown here were low-pass-filtered at 12 Hz (24 dB/Oct). The graph in (b) shows mean CDA amplitudes in the time window of 500–1200 ms after the onset of the memory display at electrodes PO7/8 as a function of memory set size, separately for the different interpretations (global, mosaic). Error bars indicate 95% (within-participant) confidence intervals.

## Discussion

The present results show that VWM load is directly influenced by processes of object completion given identical physical input. For the composite objects, the behavioral result pattern replicates previous findings (Chen et al., 2016): there was an advantage in representing globally completed over (uncompleted) mosaic interpretations in VWM, where this advantage for completed shapes decreased with an increase in the number of items that were to be memorized. An advantage for global over mosaic interpretations was also evident in the behavioral estimate of memory capacity *K*, which showed that, with the current stimulus material, a maximum of 1 to 2 objects could be successfully retained in VWM. The ERP analyses revealed larger CDA amplitudes for completed versus mosaic representations, for both set sizes, thus mirroring the effect pattern of the *K* estimate. Moreover, the differences in CDA amplitude and behavioral accuracy between completed and mosaic representations were significantly correlated. To our knowledge, these findings provide the first demonstration that VWM load – as measured by the CDA wave – is determined by processes of object completion.

The pattern for simple objects also closely replicated our previous findings (Chen et al., 2016): more regular, symmetric, global shapes led to higher performance than more irregular and complex, mosaic objects. The corresponding CDA analysis for simple objects revealed a larger amplitude for more complex mosaic shapes than for simpler global shapes, thus contrasting with the pattern observed for composite objects (for which the CDA was larger for global than for mosaic objects).

Our simple-object results may be directly compared to previous, related studies that examined how object complexity modulates VWM and the CDA amplitude. For instance, reduced behavioral performance and increased CDA amplitudes were found in a change detection task for rather complex polygon shapes as compared to simpler, colored squares (Alvarez & Cavanagh, 2004; Gao et al., 2009; Luria et al., 2010) – indicative of an increase in perceptual complexity giving rise to increasing VWM demands. That a comparable pattern of results was also found in the present experiment when comparing global and mosaic variants of the simple (non-occluded) objects, confirms that VWM maintenance demands depend on stimulus complexity: less complex global, symmetric objects engender a lower VWM load along with a reduced CDA amplitude compared to more irregular, rather complex mosaic shapes.

Over and above these established effects of perceptual complexity in VWM, our results for composite objects demonstrate a novel link between object completion and memory load. In particular, our findings show that identical perceptual input may lead to differences in the way an object is completed, depending on the prevailing simple-object context. This suggests that observers effectively use past perceptual experience – including long-term familiarity as well as short-term priming – to construct a perceptual representation that, in the global interpretation, incorporates the occluded portions of a given object (Chen et al., 2016).

Evidence for such context-dependent object completions was found in both behavioral performance and the CDA amplitude. Completion of the occluded part of an object to represent a whole renders a more elaborate but at the same time less complex memory representation. Specifically, for global objects, completion resulted in a more regular and symmetric representation, with these simpler shapes in turn yielding an improved performance accuracy compared to uncompleted but more complex shapes in mosaic-type representations (see also Van der Helm, 2014). At the neural level, we observed a sustained increase of the CDA amplitude for globally completed objects. While this is in line with the proposal that more elaborate processing, involving mnemonic resources, is required to create complete-object representations from physically specified fragments (Biederman, 1987), it also suggests that persistent mnemonic activity is required to maintain the resulting representations in a readily accessible form (see also Pun, Emrich, Wilson, Stergiopoulos, & Ferber, 2012; Ewerdwalbesloh, Palva, Rösler, & Khader, 2016). Convergent evidence for this proposal is provided by studies that used a shape-from-motion paradigm (Emrich, Ruppel, & Ferber, 2008; Pun et al., 2012). Here, too, the CDA exhibited a sustained increase in amplitude in a task that required an (integrated) object to be extracted and maintained from fragmentary perceptual information. Thus, on this view, the occluded objects engage some additional, completion-related process while being actively maintained in VWM, which is reflected in the increased CDA as compared to the non-completed mosaic representations. Completion, in turn, renders a rather simple object representation, supporting an improvement in performance relative to the more complex mosaic representation. [Of course, completion might, in principle, also generate a relatively complex, non-symmetrical shape (e.g., some form of local shape completion; see Chen et al., 2016), which does not translate into a comparable performance advantage as for the globally completed, symmetric shape.]

In sum, we interpret the observed increase in CDA amplitudes for the global interpretation to reflect the increased demand associated with the imagery process for completing the occluded object parts to represent the whole object, while the observed increase in accuracy for the completed objects derives from the simple and symmetric object representation rendered by this process. This is also reflected in the significant correlation between the completion effect in the CDA amplitude and behavioral accuracy, that is: the advantage for representing completed interpretations in VWM comes at a cost in terms of the mnemonic resources required.

Previous studies have shown that the CDA amplitude increases systematically with the number of objects stored in VWM, up to the maximum load (Vogel & Machizawa, 2004; Luria, Balaban, Awh, & Vogel, 2016, for review). Our results show that the capacity limit in the current experiment is at about 1.5 items**,** as indicated by the estimates of *K*. Comparable capacity estimates were reported previously for other geometric objects (e.g., Alvarez & Cavanagh, 2004). Owing to this relatively low capacity, at set size 4, the number of to-be-remembered items exceeds the maximum load by more than half, as a result of which only a subset of up to two items is encoded. This is reflected in the CDA being comparable between the two set sizes, that is: the available resources were already maximally invested with 2-item memory displays, so that no further resources could be mustered when the number of to-be-remembered objects was increased to 4 (see also Luria et al., 2010; Gao et al., 2009).

As concerns the limits on the storage capacity of working memory, one view proposes that VWM consists of a pool of resources that can be allocated flexibly to provide either a small number of high-quality representations or a larger number of low-quality representations (Bays & Husain, 2008); by contrast, others have suggested that the number of items that can be stored in VWM is limited and cannot change (Luck & Vogel, 1997; Zhang & Luck, 2008). Here, we found *no* evidence that observers could increase the number of representations by decreasing the quality of the representations in VWM. Instead, we show that, when presented with more objects than the maximum capacity, observers can still store high-quality representations of a subset of the objects, without retaining any information about the others. However, within the limited number of items that can be retained, a variable resource is available to represent the to-be-memorized objects (Nie, Müller, & Conci, 2017; Zhang & Luck, 2008).

In summary, the present study shows that the construction of an integrated object requires VWM resources that depend on structural information of the (to-be-) represented objects: constructing a completed representation from the physically specified parts of the stimulus involves additional mnemonic demands relative to (in terms of information content) uncompleted, mosaic representations. This argues that object representations in VWM are modulated by completion processes, in turn suggesting that the CDA does not only, or simply, reflect the passive retention of items in memory, but also some additional, active processes, or the resource demands associated with these processes, that support the integration of fragmentary parts into wholes. Thus, representing integrated wholes requires mnemonic resources, but with the constructed representations rendering simple and regular shapes, thus enhancing change detection performance.

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# 3 General Discussion

The present thesis investigated how perceptual organization, as illustrated by object completion phenomena is related to visual attention and working memory. I will briefly summarize the results of the four studies and discuss how they have helped to clarify the relationship between object completion, attention, and visual working memory.

## 3.1 Summary of findings

The first study (Chapter 2.1) investigated complementary mechanisms underlying object completion by examining the contribution of contour interpolation and surface integration in perceiving a coherent Kanizsa figure. Although neural evidence and computational models have suggested that contour and surface information relies upon distinct functional roles in the perception of illusory figures (Seghier & Vuilleumier, 2006, for a review), few studies examined their separate influences. The results show that both contour and surface completions substantially impact dot-localization sensitivity while revealing dissociable influences in object completion, thus providing support for a multi-stage model of object processing, where completion is achieved by recurrent processing loops.

The second study (Chapter 2.2) tested how the structure and regularity of an object can substantially impact the available, limited attentional resources. Previous visual search studies have demonstrated that component parts may be grouped prior to the engagement of attention (e.g., Moore & Egeth, 1997; Rensink & Enns, 1995; Conci et al., 2007a, b; Nie, Maurer, Müller, & Conci, 2016). These studies examined the allocation of selective attention across space. Our study investigated how attentional selection is influenced by perceptual grouping over time by employing an AB paradigm, in which the AB is believed to result from the temporal unavailability of attentional resources for encoding items into working memory. The results show that more regular and well-structured objects are more likely to persevere in temporal processing, leading to an attenuated AB. Conversely, an increased AB with increasing grouping strength is observed when the grouping factor is not task relevant.

The third study (Chapter 2.3) examined whether the structure of to-be-remembered objects in the case of amodal completion influences what is encoded and maintained in VWM. Previous studies provided evidence that visual search for a partly occluded target relies on a complete-object representation, suggesting that integrated object representations are available pre-attentively. However, it remains to be documented how the completed representation is processed at a later post-perceptual stage. The results have filled this gap by showing clear evidence for amodal completion in change detection sensitivity, which was particularly pronounced for objects that induce a global (i.e., symmetric) completion interpretation. Moreover, we found that completion does not occur automatically but is triggered by the available simple object context. In addition, with an increase in set size, evidence for completion is reduced, suggesting that overall capacity limitations prevent the representation of completed objects.

The fourth study (Chapter 2.4) extended the purely behavioral study regarding the relationship between VWM storage and the completion of objects by combining behavioral measures with analysis of the CDA as an electrophysiological marker of VWM load. The main finding was that the identical composite objects yielded a difference in both change detection performance and CDA amplitudes for globally completed versus mosaic interpretations, indicating that the completion process modulates the VWM load. Moreover, we found that the differences in CDA amplitude and behavioral accuracy between completed and mosaic representations were significantly correlated. While previous studies found that the CDA amplitude reflects the number and the complexity of objects maintained (Alvarez & Cavanagh, 2004; Luria et al., 2010), our study is the first to explicitly show that an additional completion process which might be considered a form of active maintenance is also reflected in the CDA during the VWM maintenance period. Overall, we support VWM models as reflecting both a continuous resource and fixed slots and that capacity limitations depend on the structured representation of to-be-remembered objects.

## 3.2 Underlying mechanisms of object completion

The identification of relevant perceptual units, or objects that are present in the visual ambient array is a fundamental operation of human vision and a basis in any cognitive task. A prime example to demonstrate such mechanisms of object integration is the Kanizsa figure, in which perceptual boundaries and perceptual surfaces compute complementary properties. The first study (Chapter 2.1) examined the modulation of the dot-localization performance by the relative contour and surface groupings and provides insights into how the illusory figures are completed and identified.

Both the groupings of contour and surface alter higher cognitive processes involved in the visuospatial judgments (see also Weidner & Fink, 2006), with the highest dot-localization sensitivity for (complete) Kanizsa figures, followed by Shape consisting of both partial surface and contour information, and Contour presenting only partial contour information, and the lowest sensitivity for Baseline without any completion. When it was not possible to perceive explicit, definitive contours of the illusory objects in the occluded stimuli or in stimuli with smoothed edges, observers nevertheless appeared to perceive the continuation of the surface behind the pacmen or the salient region filled by the surface information and increased their perceptual sensitivity for the illusory shape. It is the first time to explicitly demonstrate that both the completion of illusory contours and surfaces provide essential contributions to the formation of illusory Kanizsa figures while revealing dissociable influences in object completion.

These findings clearly indicate that illusory contours and the corresponding surfaces are computed by separate mechanisms that do not necessarily depend on each other (see also Dresp & Bonnet, 1991; Dresp, Lorenceau, & Bonnet, 1990; Rogers-Ramachandran & Ramachandran, 1998), supporting recurrent models of completion, where the completion of illusory figures results from a series of feedforward and feedback loops, with processing of distinct attributes of an object in parallel at various levels in the visual hierarchy (Lamme & Roelfsema, 2000; Roelfsma et al., 2002; Kogo et al., 2010; Kogo & Wagemans, 2013). These interpretations are consistent with the neurophysiological findings, which indicate that recurrent feedback and feedforward information flow between higher-tier large receptive field regions and lower-tier small receptive field regions can facilitate the perception of an illusory figure (e.g., Stanley & Rubin, 2003; Shpaner et al., 2013). The results also agree with previous behavioral observations that both processes of surface and contour grouping are available pre-attentively (e.g., Conci et al., 2009).

The properties of a scene are represented by the surface processing stream and a key step in representing a surface is ‘filling-in’ (Grossberg, 2000). Filling-in behaves like a diffusion of brightness across space until illuminant-discounted signals fill-in an entire region (Grossberg & Todorovic, 1988; Arrington, 1994; Paradiso &

Nakayama, 1991). Signals from the boundary stream to the surface stream define the regions within which filling-in is restricted (Grossberg, 2000). Following this line of reasoning, the final, completed object then relies on the interactions between surfaces and contours, which either involves recurrent feedback iterations with the construction of a surface prompting the interpolation of illusory contours, or the invisible boundaries would indirectly be completed through their interaction with the surface processing output.

### 3.3 Grouping, visual attention and working memory

One of the goals of this doctoral thesis was to investigate the relationship between grouping and visual attention. The AB phenomenon shows that the detection of the second target is often hampered because task-critical processing resources are still occupied by the first target. This reflects limitations in the consolidation of multiple objects in rapid succession. Since a large amount of evidence has shown that grouping leads to a more efficient integration of separate, individual parts, thus, leading to some form of "compression" of visual information, reducing the required resources (Brady & Tenenbaum, 2013; Conci & Müller, 2014; Töllner, Conci, & Müller, 2015), the grouping attributes of Kanizsa figure should largely facilitate the consolidation process. As shown in the results of study 2 (Chapter 2.2), when grouping was task relevant, it was found to enhance the efficiency of processing, leading to an associated reduction of attentional demands. A comparable benefit was also revealed at a post-attentive stage in short-term memory until the execution of a response.

Kanizsa figures generates a salient structure and have a processing advantage that arises relatively early, at the initial stage of perceptual coding (Rauschenberger & Yantis, 2001b; Senkowski et al., 2005). In previous visual search tasks, Kanizsa figures provide a non-informative spatial 'cue' facilitating the target response when the target is presented inside the Kanizsa figure (Senkowski et al., 2005), as the Kanizsa figure leads to an amplification of spatial attention at the location of the figures. In an AB paradigm, the target is quickly gone by the time attention is disengaged from the distractor. The salient Kanizsa figures, in turn, are relatively resistant against decay and are less likely to be erased by the subsequently presented item in the RSVP stream. Therefore, these figures are more efficiently consolidated into working memory in spite of the limited capacity available. On the other hand, when grouping is unrelated to the task-relevant target, attention is automatically drawn to the irrelevant grouped configuration at the target location and disengaging from this distractor impairs target processing (see also Bertleff, Fink, & Weidner, 2017).

In addition, we observed that it is difficult to segregate a continuous, rapid stream of visual information into discrete events in time. The object representations are easily influenced by the shapes of other objects in close temporal proximity. It could lead to either an increased AB because of integration in structure properties (see also Hommel & Akyürek, 2005) or an attenuated AB because of a repetition of the sequential objects (see also Raymond, 2003; Conci & Müller, 2009).

Some studies suggest that all visual information needs to pass through a limited-capacity stage before it can be explicitly reported (Joseph, Chun, & Nakayama, 1997; Braun, 1998). Conversely, increasing the efficiency with which the stimulus is encoded reduces its attentional load and therefore leads to an elimination of task interference (Braun, 1998; Joseph, Chun & Nakayama, 1998). Despite the fact grouped object exhibited an increased coding efficiency and an associated reduction of attentional demands, which overall resulted in an attenuated AB, we nevertheless observed an AB for the grouped T2, indicating that the detection of the grouped object could not be processed completely independently of attention.

Therefore, with the AB paradigm, we concluded that the structure and regularity of an object can substantially impact the post-perceptual process by drawing attentional resources. However, object integration nevertheless requires a certain amount of attentional resources.

### 3.4 The role of completion in visual working memory

The current thesis further elucidates how amodal completion is achieved in order to generate a stable representation in VWM. Within an appropriate context, global (but not local) completion is the favored interpretation of an occluded object when global and local processes lead to qualitatively different completions. The active maintenance of a completed object requires mnemonic resources, as indicated by reduced memory performance when capacity was exceeded (Chapter 2.3) and increased CDA amplitudes (Chapter 2.4). Therefore, visual mnemonic representations crucially depend on the structure of to-be-remembered objects.

An analysis of the composite objects (i.e. with a constant visual input) showed evidence for a completion process to render the partly occluded stimuli as a coherent, complete-object representation. Such completion process is mainly influenced by the contextual information provided by the intermixed simple-object trials. The mosaic context supports a perceptual representation of the cutout (i.e., mosaic) fragment, whereas the global and local contexts support relative globally and locally completed objects. Without any consistent context, no completion is observed at all for the composite objects (Chapter 2.3). These results are in accordance with parallel processing of mosaic and occlusion interpretations (see also Bruno et al., 1997; Rauschenberger et al., 2004).

The completed shape needs to be retained during the delay period, i.e. until participants are prompted to make a response. Keeping such a completed object representation active in VWM requires some additional resources that may be comparable to other forms of mental imagery. To support this idea, it has, for instance, been demonstrated that elaborate processing is needed in order to integrate fragments into a complete whole, and such elaborate processing is reflected by persistent activation to maintain the objects in VWM (Biederman, 1987; Emrich, Ruppel, & Ferber, 2008). In Study 4, additional neural processing as reflected by the CDA component may relate to object completion in order to successfully generate and maintain a global representation of the partially occluded objects (see also Ewerdwalbesloh et al., 2016; Sauseng et al., 2005). In this view, the CDA might be considered as a form of active maintenance, that is an additional, active processes associated with the processes, that support the integration of fragmentary parts into wholes.

Concerning the nature of WM capacity, both slots and resource accounts are supported based on the current findings, as is indicated by the results that observers can store high-quality representations of an object subset, without retaining any information about the other objects when presented with a memory set size beyond the maximum capacity. However, within the maximum number of items, the VWM load is variable to represent the structural attributes of the to-be-memorized objects. This suggests that memory resolution is variable within a narrow range – a pattern that cannot be explained in terms of a general resource pool but supports an account of a small set of discrete, yet flexible representations (see also Zhang & Luck, 2008; Zhang & Luck, 2011).

## 3.5 Concluding remarks

In this thesis I presented behavioral and neurophysiological evidence of object completion effects in attention and memory that are currently in the focus of research and still not well understood. We evaluated object completion mechanisms by investigating how grouping of illusory contours and surfaces modulates higher cognitive processes involved in visuospatial judgments, and reported evidence for an interplay between object integration and attention. Further, the results also provide evidence for a modulation of working memory by completion processes. The current thesis therefore indicates that completion is not simply an “early” process, which terminates after initial perceptual processing, but signatures of object integration can also be demonstrated at higher levels of cognitive processing.

Specifically, object completion can reveal complementary functions that lead to either object compression or to an increase of the represented object detail. For instance, completion in the Kanizsa figures leads to fewer individuated items, such that separate pacmen elements are combined to form a coherent object, which is more simple and reduced in complexity than the corresponding component parts. By contrast, completion of occluded objects increases the information details of the respective representation and such a “richer” representation of a perceptual input is constructed. Both variants of grouping can improve performance but they reveal a crucial difference in terms of their functional role as demonstrated by the required resources for attentional and working memory processes. In light of these findings, it is important to take the structures of items and the relative grouping factors into consideration when evaluating cognitive performance of humans in visual tasks.

It might be interesting for future work to discern the role of specific brain region in the processing of grouping and to illustrate whether such processing is purely driven by visual patterns in a bottom-up manner or whether grouping also requires some top-down involvement. Methodological approaches that combine the behavioral assessment with spatially and temporally sensitive measures of brain activity could be particularly fruitful in this regard.

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# Curriculum Vitae

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# List of Publications

## Journal articles

**Chen, S.**, Töllner, T., Müller, H. J., & Conci, M. (in press). Object maintenance beyond their visible parts in working memory. *Journal of Neurophysiology*. DOI: 10.1152/jn.00469.2017.

Hu, X., **Chen, S.** (Co-first Authors), Huang, C. B., Qian, Y., & Yu, Y. (2017). Frequency-dependent changes in the amplitude of low-frequency fluctuations in patients with Wilson's disease: a resting-state fMRI study. *Metabolic Brain Disease, 32*(3), 685-692.

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Hua, M., Han, Z. R. (Co-first Authors), **Chen, S.**, Yang, M., Zhou, R., & Hu, S. (2014). Late positive potential (LPP) modulation during affective picture processing in preschoolers. *Biological Psychology, 101*, 77-81.

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*Engineering, 24*(4), 253-258. (In Chinese)

Chen, Y., Zhao, X., Huang, J. H., **Chen, S.**, & Zhou, R. L. (2011). Effects of mindfulness meditation on emotion regulation: theories and neural mechanisms. *Advances in Psychological Science, 19*(10), 1502-1510. (In Chinese)

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**Chen, S.**, Zhang, Q. N., & Zhou, R. L. (2010). The influence of degree of relatedness between the target cue and intention on prospective memory. *Studies of Psychology and Behavior*, *8*(1), 70-75. (In Chinese)

**Chen, S.**, & Zhou, R. L. (2010). Prospective memory needs strategic control processing: evidence from eye movements. *Acta Psychologica Sinica*, *42*(12), 1128-1136. (In Chinese)

**Chen, S.**, & Zhou, R. L. (2010). Age-related declines in prospective memory: Modulation of the prospective and retrospective components. *Acta Psychologica Sinica*, *42*(6), 640-650. (In Chinese)

**Conference abstracts**

**Chen, S.**, Glasauer, S., Müller, H. J., & Conci, M. (2017, August). Filling-in and contour interpolation in Kanizsa configurations. Talk presented at the European Conference on Visual Perception 2017, Berlin, Germany. Retrieved from URL: *http://journals.sagepub.com/page/pec/collections/ecvp-abstracts/index/ecvp-2017* on Monday August 28th.

**Chen, S.,** Töllner, T., Müller, H. J., & Conci, M. (2016, August). Object maintenance beyond their visible parts in working memory: Behavioral and ERP evidence (meeting abstract). *Perception, 45*, 168-169.

Hua, M., **Chen, S.,** Yang, M., & Zhou, R. (2013, January). Association between late positive potential during emotional picture processing and emotion regulation competence in preschoolers (meeting abstract). *Journal of Cognitive Neuroscience*, 95-96.

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## Eidesstattliche Versicherung/Affidavit

Hiermit versichere ich an Eides statt, dass ich die vorliegende Dissertation "Object completion effects in attention and memory" selbstständig angefertigt habe, mich außer der angegebenen keiner weiteren Hilfsmittel bedient und alle Erkenntnisse, die aus dem Schrifttum ganz oder annähernd übernommen sind, als solche kenntlich gemacht und nach ihrer Herkunft unter Bezeichnung der Fundstelle einzeln nachgewiesen habe.

I hereby confirm that the dissertation "Object completion effects in attention and memory" is the result of my own work and that I have only used sources or materials listed and specified in the dissertation.

München, den

Munich, date 21.12.2017 Unterschrift/signature Siyi Chen

## Author Contributions

### Chapter 2.1

The author of this dissertation was primarily involved in designing and programming the experiment, collecting and analyzing the data, creating plots, interpreting the results and in writing of the manuscript.

Stefan Glasauer contributed to the data analysis and to the interpretation of the results. He also commented on the manuscript.

Hermann Müller helped with the interpretation of the results. He commented on and helped revising the manuscript.

Markus Conci conceived and supervised the project, participated in designing the experiments and interpreted the results. He also commented on and helped revising the manuscript.

### Chapter 2.2

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Hermann Müller contributed to the interpretation of the results. He commented on and helped revising the manuscript.

Markus Conci conceived and supervised the project, participated in designing the experiments and interpreted the results. He commented on and helped revising the manuscript.

### Chapter 2.3

A version of this chapter has been published as Chen, S., Müller, H.J. & Conci, M. (2016). Amodal completion in visual working memory. *Journal of Experimental Psychology: Human Perception and Performance, 42*(9), 1344-1353.

The author of this dissertation designed and programmed the experiments, collected and analyzed the data, created plots, interpreted the results and wrote the journal article.

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**Chapter 2.4**

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The author of this dissertation designed and programmed the experiment, collected and analyzed data, created plots, interpreted the results and wrote the manuscript.

Thomas Töllner helped with the data analysis and with interpreting the results, and he commented on the manuscript.

Hermann Müller helped with the interpretation of the results, and he commented on and helped revising the manuscript.

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The above contributions to the doctoral thesis of Siyi Chen are all correct as stated above.

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