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Research Report

Attention capture by salient object groupings in the neglected visual field

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ABSTRACT

The integration of fragmentary parts into coherent whole objects has been proposed either to rely on the availability of attentional resources or to arise automatically, that is, from preattentive processing (prior to the engagement of selective attention). In the present study, these two alternative accounts were tested in a group of neglect patients with right-hemisphere parietal brain damage and associated deficits of selective attention in the left (visual) hemispace. The reported experiment employed a search task that required detection of targets in the left and/or right hemifields, which were embedded in configurations that consisted of variants of Kanizsa figures. The results showed that a salient, grouped Kanizsa triangle presented within the unattended, left hemifield can substantially improve contralesional target detection, though the very same triangle configuration does not facilitate target detection in the impaired hemifield when presented together with an ipsilesional, but non-salient (i.e., structurally non-integrated, isolated) target. That is, attention is captured by the grouped object in the impaired hemispace only when it is not engaged in the processing of an (isolated) object in the attended hemispace. This demonstrates that both part-to-whole-object integration and search guidance by salient, integrated objects crucially require attentional resources.

1. Introduction

Natural environments usually contain multiple sources of information, several of which may be simultaneously task-relevant. However, given the limited capacity of the visual system, it is essential to structure and organize the complex visual input into meaningful perceptual units for efficient processing and adequate interaction with the environment. One mechanism involved in this is perceptual grouping,

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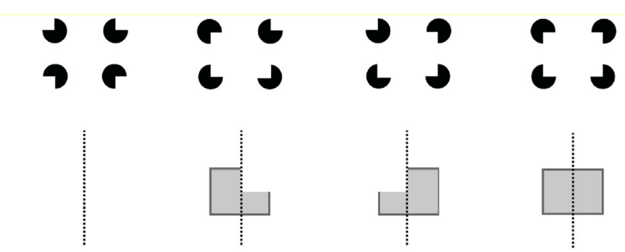
supporting the integration of fragmented image parts into complete objects. Koffka (1935) and Wertheimer (1923) were the first to describe grouping processes in terms of organizational principles, or 'laws', that govern the formation of higher-order units. In this view, object integration organizes non-contiguous parts into coherent whole objects, or 'Gestalten', by linking edges and segments according to principles of collinearity and closure (for a review see Wagemans et al., 2012). One prominent example is the "Kanizsa figure" (Kanizsa, 1976), where the arrangement of several disks with missing quarter-segments creates a vivid impression of an illusory object, such as the shape of a square, that lacks a corresponding physical object (see Fig. 1, right). Kanizsa figures thus illustrate how wholes are generated from fragmentary visual information.

The organization of the natural environment by means of perceptual grouping appears to operate in a fairly effortless manner and provides rather unambiguous interpretations of objects in our ambient array. Yet, it has been debated whether such grouping operations reflect a low-level automatic, "pre-attentive" process or whether object integration arises from higher-level cognitive functions that depend on the engagement of attention. That is, opposing viewpoints postulate that object integration arises either before or after attention is allocated to a given, to-be-integrated object. In fact, whether or not attention is critical for the perception of complete objects has led to the formulation of influential, opposing theories of visual perception (Driver & Baylis, 1998; Treisman & Gelade, 1980), and this question has since remained a controversial issue. To contribute to a resolution, in the current study, we tested the role of attention for the integration of parts into wholes by assessing object completion mechanisms in neglect patients, who typically exhibit deficits of selective attention in the left hemispace following right-hemispheric brain damage. Our experiment presented a visual search task requiring detection of target items in the left and the right visual field, which were embedded in configurations that systematically varied perceptual grouping in the two hemifields (e.g., a Kanizsa triangle in the left, or right half of the display). This setup was designed to determine whether perceptual grouping in the attended vs. unattended hemispace of the neglect patients would be equally efficient in modulating target detection performance.

As in the current study, in many previous studies, a key approach for investigating whether selective attention is required for visual object integration has been to assess brain-damaged patients with impaired attentional functioning. For instance, impairments of selective attention have been demonstrated in patients suffering from visual hemi-neglect and associated extinction behavior (Driver, 1995; Kerkhoff, 2001). Contralesional visuo-spatial neglect is characterized by the failure to attend, respond adequately, or orient voluntarily to stimuli in the contralesional hemispace (Karnath, Milner, & Vallar, 2002; Kerkhoff, 2001). These behavioral deficits typically occur in the left hemispace—as a result of right-hemispheric brain lesions, predominantly in the right inferior parietal cortex (in particular, in the angular and supramarginal gyrus) and in the right temporoparietal junction (Karnath et al., 2002; Kerkhoff, 2001). Importantly, in these patients, failure to process visual information in the left hemispace cannot be explained by primary sensory or motor deficits; rather, the observed deficits in performance result



	Ungrouped	Rightward	Leftward	Kanizsa
Mattingley et al. (1997)	17%			78%
Conci et al. (2009)	23%		79%	82%
Conci et al. (2018)	35%	48%		72%
	✗	✗	✓	✓

Fig. 1 — Examples of stimuli as used in previous studies (Conci et al., 2009, 2018; Mattingley et al., 1997), depicting bilateral configurations of ungrouped (left), partially grouped (middle), and complete Kanizsa figures (right). Partial groupings could either extend into the right or the left hemifield. For each configuration, the arrangement of inducers is depicted in the top row, along with an (idealized) illustration of the resulting integrated object in the bottom row. In addition, for each of these configurations, the associated mean percentages of correct detections of left-sided (Mattingley et al., 1997) and, respectively, bilateral (Conci et al., 2009, 2018) targets are provided. Red cross and green check marks illustrate whether the respective configurations were associated with substantial extinction behavior or, respectively, a reliable reduction of extinction behavior.

from a unilateral impairment in selective visual attention (Kerkhoff, 2001; Posner & Driver, 1992). A phenomenon that is associated with visual neglect is extinction behavior, which is also often classified as a mild form of neglect (Umarova et al., 2011). Extinction manifests in a failure to detect a contralesional stimulus when this is presented together with a second, ipsilesional stimulus, despite intact processing of single, unilateral stimuli in either hemispace (Kerkhoff, 2001). Thus, both visual extinction and neglect appear to arise from a competitive disadvantage of selection from the contralesional hemispace due to disrupted processes of selective attention (Baylis, Driver, & Rafal, 1993; Humphreys, Romani, Olson, Riddoch, & Duncan, 1994). The deficit, however, is relative rather than absolute, indicative of fewer attentional resources being allocated to the contralesional than to the ipsilesional side (Bays, Singh-Curry, Gorgoraptis, Driver, & Husain, 2010; Conci, Gross, Keller, Müller, & Finke, 2018; Gögler, Finke, Keller, Müller, & Conci, 2016).

Early findings from neglect and extinction studies support the view that object integration is achieved prior to the engagement of attention (Driver & Baylis, 1998; for a review see Humphreys, 2016; Scholl, 2001), thus arguing against the notion that attention must first be allocated to a given stimulus to enable the integration of fragmented image parts into a coherent whole object (e.g., as suggested by feature integration theory; Treisman & Gelade, 1980). A prominent example supporting such an "object-based" view of attention was provided by Mattingley, Davis, and Driver (1997). In their study, a patient with parietal brain lesions and associated extinction behavior was presented, in a series of experiments, with variants of Kanizsa figures that give rise to the perception of a grouped, illusory object. The typical experiment presented a sequence of displays with four disks arranged to form a square around central fixation. On each trial, quarter-segments were briefly removed from the disks either from the left, from the right, from both sides, or not at all. The task was to detect the side of the offsets. Removal of these segments on either the left or the right side of the display (i.e., presentation of unilateral left or right targets) did not impair performance.[1] However, there was severe extinction when the segments were removed from both sides (bilateral targets) under conditions in which these bilateral segments were oriented such that no grouping emerged (see Fig. 1, Ungrouped): the patient failed to detect more offsets on the left side when these were presented together with offsets on the right side (compared to unilateral left presentations). Crucially, extinction was much less severe when the disks in two hemifields formed a coherent Kanizsa square across the two sides (see Fig. 1, Kanizsa). That is, the typical extinction behavior vanished when bilateral segments could be grouped into a complete object across both hemispaces (see also Conci et al., 2009). The finding that the formation of integrated objects was preserved in the extinction patients despite severe attentional deficits was taken as evidence that object completion occurs without the engagement of attention (see also Vuilleumier, Valenza, & Landis, 2001).

Further support for object integration occurring at preattentive processing stages comes from studies with healthy observers, which concluded that an integrated object (e.g., a Kanizsa figure) may act as a salient cue that automatically attracts attention independently from the observer's goals (e.g., Kimchi, Yeshurun, Spehar, & Pirkner, 2016; Rauschenberger & Yantis, 2001; Senkowski, Rottger, Grimm, Foxe, & Herrmann, 2005; Wiegand et al., 2015). For example, Kimchi et al. (2016) asked their participants to detect the presence of a target (a Vernier stimulus) within an array of circular elements. On some of the trials, a subset of these elements was organized such that they formed a coherent whole object (a Kanizsa figure), and the target could appear either inside or outside of this grouped object. Faster responses were observed when the target appeared within the illusory figure, as compared to when no grouped object was presented. Moreover, responses were slowest when the target was presented outside the grouped object. This modulation of target detection latencies was obtained even though the grouped object was completely task-irrelevant and not predictive of the target location—which was taken to indicate that illusory figures can capture attention automatically. Moreover, the critical reaction time effect was found to scale with the strength of perceptual organization, indicating that more salient illusory figures are more potent attractors of attention (see also Conci, Müller, & von Mühlenen, 2013).

Besides attentional capture effects in healthy observers, the assessment of patients with visual hemi-neglect provides a valuable approach for investigating whether complete objects are integrated automatically, that is, without the engagement of focal attention. If grouping is accomplished without the engagement of attention, then neglect patients should show effects of such preattentive grouping. Accordingly, one would expect salient, attention-attracting groupings in the left, neglected hemispace to influence visual search performance comparably to groupings in the right hemispace. However, recent studies with visual neglect patients yielded no consistent evidence of such a grouping-dependent modulation of attentional priorities in the left hemispace. For instance, Gögler et al. (2016) had extinction patients perform a visual search task that required them to discern the presence (vs. absence) of a Kanizsa-figure target presented alone or together with a task-irrelevant nontarget. For the critical target-present trials, the results showed RT costs in detecting the fully grouped illusory object when the nontarget induced a distracting shape grouping, but only if the latter emerged in the attended (right) hemifield. Conversely, there was no comparable cost when the distracting shape grouping was presented in the unattended (left) hemifield. This pattern suggests a competitive advantage only for right-grouped—that is: attended—object parts. Moreover, in addition to replicating Mattingley et al.'s (1997) critical finding—of a reduction of extinction when bilateral targets could be integrated to form a Kanizsa square —, Conci et al. (2009, 2018) varied the grouping

[1] Unilateral left displays typically do not lead to extinction behavior even though the circles with removed quarter-segments on the left, unattended side (the targets) are presented together with two full circle placeholders on the right, attended side (Mattingley et al., 1997; Conci et al., 2009, 2018). Of note, though, the placeholder circles are not directly task-relevant (i.e., the target is a gap in the circle, rather than the circle itself) and thus do not compete strongly for attentional resources. Given this, the full circles per se do usually not induce extinction in this paradigm.

strength of the presented Kanizsa configurations. When the patients were presented with “partial” groupings such that object completion emerged primarily from the attended hemifield (see Fig. 1, Leftward), the degree of extinction was substantially reduced, to a level comparable to that with “fully” grouped Kanizsa figures (Fig. 1, Kanizsa; Conci et al., 2009). In contrast, when (in a follow-up study: Conci et al., 2018) patients were again presented with partial groupings, but with the completed object emerging primarily from the unattended hemifield (in the critical condition), the grouping was not successful to remedy visual extinction behavior (see Fig. 1, Rightward). Together, these studies show that the grouping direction—that is, whether object integration proceeds from the intact, attended hemispace, or from the unattended, impaired hemispace—determines whether or not a reduction of extinction becomes manifest. Conci et al. (2018) took this to suggest that attention may provide some “glue” that binds separate parts into coherent objects: In extinction and neglect patients, this “glue” seems to be lacking in the unattended hemispace, leading to impaired object integration processes, as a result of which Kanizsa figures are processed comparable to non-integrated, non-salient object configurations.

While these results appear to indicate—in contrast to many previous studies—that attention is crucial for object integration, the reported findings can only be considered preliminary evidence. Of note, almost all previous studies investigating grouping in extinction patients presented configurations that extended across both hemifields (see examples above). Conci et al. (2009, 2018) presented “partial” groupings where completion processes would originate from either the attended or the unattended hemifield. Nevertheless, these configurations did also extend across both hemifields (see Fig. 1) and so might have instigated some cross-hemispheric linkage in the first place that, in turn, fosters the subsequent spreading of attention from one hemifield to the other. It thus remains unclear whether hemifield-specific object groupings—that is, configurations that do not afford attentional spreading across hemifields along the grouped object—would yield a comparable result pattern to that found in the combined Conci et al., 2009 and 2018 studies, namely, that a substantial reduction of extinction depends on the availability of attention. The primary aim of the present study was to address this issue, by introducing and comparing object groupings that were restricted to the attended versus the unattended hemispace of neglect patients. Moreover, in comparing hemifield-specific grouping processes within the attended versus the unattended hemifield, a secondary aim was to examine for potential variations in performance in a within-subjects design (instead of the comparison between separate groups that participated in the two Conci et al., 2009 and 2018, studies), so as to ensure that any differential effects between the two conditions cannot not be attributed to accidental differences in the samples of patients tested.

To this end, new variants of Kanizsa figures were designed and presented in the impaired and the attended hemifields, in a single group of patients suffering from visual extinction. Critically, rather than implementing square configurations as in previous studies (Conci et al., 2009, 2018; Mattingley et al., 1997), the new variants were composed of four disk elements arranged in diamond form—with the patients being required to indicate whether segments were removed from the left disk, the right disk, from both disks, or not at all, while ignoring the (distractor) disks at the top and bottom of a given configuration (see Fig. 2A). Compared to the (square) stimuli employed in previous studies, this new design provided more experimental control over the exact region of space where an illusory figure would emerge, essentially permitting grouping to be varied independently within each half of the display.

To elaborate, groupings consisted of either an illusory Kanizsa figure (‘diamond’) that spread across both hemifields, or an illusory figure (‘triangle’) that was confined to only one, the left or the right, hemifield. Similar to previous studies (Conci et al., 2009, 2018; Mattingley et al., 1997), and as depicted in Fig. 2B, a complete illusory Kanizsa diamond integrated all displayed quarter segments into a single, coherent object. In the ungrouped configuration, the individual cut-out segments were not linked into a corresponding bilateral grouping. We expected to replicate previous findings, namely, that extinction behavior would be less severe when bilateral stimulus configurations could be grouped to elicit the perception of a salient, diamond-like Kanizsa figure compared to ungrouped configurations. In the left- and right-triangle configurations, by contrast, a Kanizsa figure, giving rise to a salient triangle grouping, was presented only within one half of the display, that is: this grouping was not connected with the quarter-segment in the opposite display half. Importantly, the triangle groupings always proceeded from the central midline, thus confining grouping of a salient shape to either the intact, attended (left) or to the impaired, unattended (right) hemispace. This distinguishes the present grouping variations from the square configurations used in the previous studies (see Fig. 1). Accordingly, comparison between these two conditions permitted us to test the efficiency of *hemifield-specific* grouping and its associated attention-attracting effect in neglect/extinction patients. The condition of major theoretical interest in this respect is that with a Kanizsa triangle in the unattended, left hemifield This condition makes it possible to test whether the presence of a salient grouping within the impaired hemispace can improve the detection of a contralesional target—in particular, when attention is engaged in processing an additional target in the ipsilesional, that is, attended hemispace.

2. Materials and methods

2.1. Participants

Eleven patients (eight males, $M = 64.5$ years, $SD = 8.29$, range = 53–73 years), recruited from the Neurological Rehabilitation Clinic in Bad Feilnbach, Germany, took part in the experiment. Ten of the patients suffered from a stroke and one from a craniocerebral injury. Inclusion criteria for participation in the experiment were clinical signs of visual hemi-neglect according to the neurological examination and the reports of the patient’s neuropsychological therapists, and impaired performance on a minimum of two out of the six neglect subtests of the Behavioral Inattention Test (BIT; Wilson, Cockburn, & Halligan, 1987). BIT sum scores were

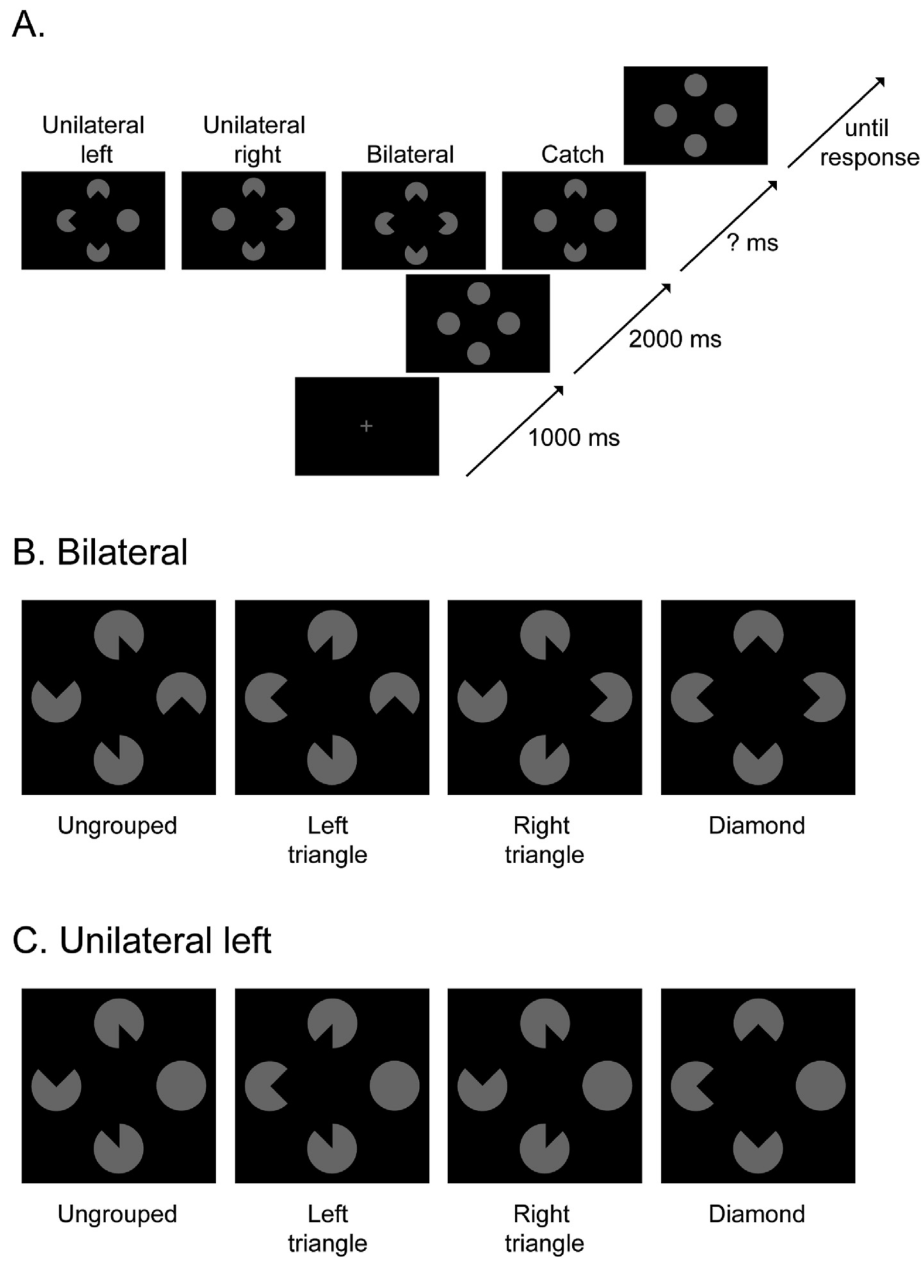


Fig. 2 – (A) Example trial sequence. Each trial started with the presentation of a fixation cross for 1000 ms, followed by a pre-mask display shown for 2000 ms. Next, a Kanizsa-type configuration was presented with removed quarter segments from the top and bottom, and from either the left side, the right side, both sides, or no side (with presentation times adjusted individually for each observer). Finally, a post-mask display was presented until a response was given. (B) Examples of the different types of object groupings presented in bilateral target displays (i.e., displays containing target cut-out segments in both hemifields): In the diamond configuration, a complete illusory figure was induced (right panel). The right triangle condition (middle-right panel) presented an illusory triangle in the right hemifield, and the left triangle condition (middle-left panel) an illusory triangle in the left hemifield. The ungrouped configuration (left panel), which did not induce any illusory figure, served as a baseline. (C) Corresponding examples of the various types of object groupings in unilateral left target displays, in which a cut-out *target* segment was presented only in the left hemifield. Note, that examples of all object groupings for all four types of target displays (i.e., also for all variants of unilateral right and catch displays) can be found in the Supplement.

computed for each patient. Based on these scores, the neglect was rated severe to moderate in four patients (BIT score < 100), mild in three patients (BIT score > 100), and only residual in four patients who scored above the BIT cut-off criteria of 129 at the time of testing. The patients were tested within 4–32 weeks post-injury. In all but two patients, intelligence quotient (IQ) scores were estimated using the German Multiple-Choice Vocabulary Test (Mehrfachwahl-Wortschatz-

Intelligenztest, MWT-B; Lehrl, 2005) and found to be in the normal range. In two patients, an assessment of the IQ scores was not possible because they were either non-native German speakers or had problems to concentrate on the IQ test after having been tested for ~1.5 h in the formal experiment. All participants, however, fully understood the instructions and the experimental procedure. Table 1 summarizes the clinical and demographic data of all patients.

Lesion locations were identified by means of perfusion computer tomography (CT), which was recorded 4–32 weeks after the acquired brain damage and prior to testing. Lesions were mainly confined to the right hemisphere and clustered in inferior-parietal and/or temporo-parietal areas (see Fig. 3). Note that a CT scan was not available from one patient (J.W.), but according to the medical reports from the acute clinic, J.W. actually showed neglect-typical right-parietal lesions as displayed in Fig. 3.

The experimental procedure was approved by the local ethics committee (Faculty of Psychology & Pedagogics, Ludwig-Maximilians-University, Munich), and written informed consent according to the Declaration of Helsinki was obtained from all participants. Our sample size was based on previous, related work and comparable to our previous studies (Conci et al., 2009, 2018). In fact, the sample of neglect/extinction patients was larger than the samples in the majority of the neuropsychological studies on perceptual grouping cited in this article.

2.2. *Apparatus and stimuli*

The experiment was programmed using the Psychophysics toolbox (Kleiner, Brainard, & Pelli, 2007) in combination with Matlab (MATLAB, 2017). During the experiment, the head of the participant was stabilized by a forehead and chin rest, positioned approximately 57 cm from a 17-inch monitor (1024 × 768 pixels screen resolution, 70-Hz refresh rate). Eye movements were monitored by the experimenter using a light-sensitive web-camera. Whenever the patient lost central fixation, the experimenter verbally instructed the participant to re-fixate the screen center. Neglect/extinction patients often show a tendency to overtly shift their eye gaze towards the unimpaired visual field, and this control procedure was intended to minimize these types of eye movements. The experiment was conducted in a sound-attenuated room that was dimly lit.

Stimuli consisted of four gray placeholder disks (3.81 cd/m2), each of a diameter of 1° of visual angle, which were presented against a black background (.01 cd/m2). The disks were arranged in diamond form subtending 3.5° × 3.5°, and their distance from the central fixation cross was 1.3°. There were four different types of target display: *unilateral* left displays consisted of two central disks (one above and one below fixation) and the disk to the left of fixation, which all had a segment cut out whereas the right disk was complete (i.e., without cut-out section); in *unilateral* right displays, segments were removed from the right and the central disks, and the left disk was complete. In *bilateral* displays, all four circles were presented with cut-out (quarter) segments. Finally, in catch trials, only the central (i.e., the top and bottom) disks had cut-out sections, whereas the left and right disks were both complete. Note that catch trials were presented to obtain a measure for guessing. Examples of all four types of target display are depicted in Fig. 2A.

For each of these types of target display, four object grouping variants were generated through systematic changes of the orientation and size of the cut-out segments (see Fig. 2B for examples of these types of object groupings in bilateral target displays). For the diamond configuration (Fig. 2B, right), the segmented disks were arranged such that a complete Kanizsa-type illusory diamond emerged across both hemifields from the inward-facing indents in the disks (Chen, Glasauer, Müller, & Conci, 2018). In addition, two variants of this configuration presented a complete Kanizsa-type illusory triangle, either in the right hemifield (right triangle, Fig. 2B, middle-right), or in the left hemifield (left triangle, Fig. 2B, middle-left). Note that the cutout segment in the other hemifield was presented such that it did not integrate with the triangle, facing randomly either to the top or bottom. Finally, ungrouped configurations were arranged pseudo-randomly such that no illusory figure emerged within the left or the right hemifield: the disks with missing quarter-segments on the left and right faced up and down, and the cut-out segments in the top and bottom disks faced to the left and right, respectively (see Fig. 2B, left).

Table 1 – Clinical and demographic data of the patients.

	Sex	Age	Handedness	Injury type	IQ score	BIT score	TSI (weeks)	Presentation time (ms)
Patients								
J.W.	m	73	r	MCA	94	97	15	650
G.F.	f	64	r	MCA	104	141	7	250
T.C.	m	73	r	MCA	94	91	4	500
H.U.	m	71	r	MCA	94	141	7	15
M.S.	f	53	r	MCA	81	128	5	900
R.L.	f	71	r	MCA	–	139	6	300
J.B.	m	61	r	MCA	–	112	9	200
E.B.	m	54	r	MCA	101	40	32	1000
R.B.	m	53	r	CCI	95	126	19	1500
B.K.	m	73	r	MCA	100	94	4	2000
K.R.	m	64	r	MCA	95	136	12	300

Abbreviations. BIT = behavioral inattention test, CCI = cortical contusion injury, f = female, m = male, MCA = right medial cerebral artery infarction, r = right, TSI = time since injury.

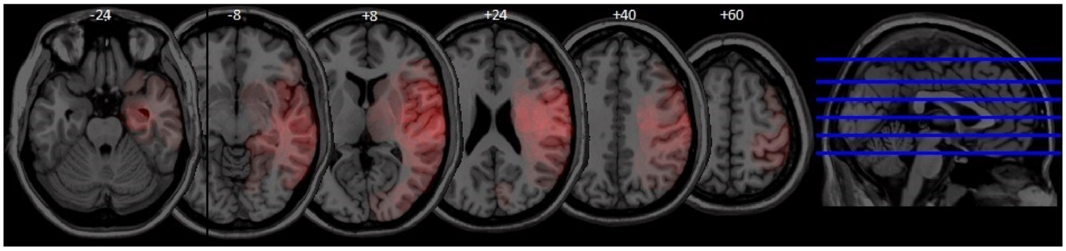


Fig. 3 – Lesion location overlap for N = 10 extinction patients, reconstructed for 6 transversal slices (left) and their positions in sagittal orientation (right). Numbers above the slices depict the z-score in Talairach coordinates. Higher overlaps are shown in darker red.

Of note, the various types of object groupings were always constructed and labeled on the basis of complete, bilateral displays (see Fig. 2B), that is, displays in which all four inducers were presented with cut-out segments. As described above, in unilateral displays, cut-out segments would be presented at the top and bottom positions and on either the left side (unilateral left display) or the right side (unilateral right display) – with the respectively other side containing a full circle. Accordingly, in some configurations, a given grouping would not emerge. For instance, in unilateral left displays, any right triangle grouping would be obstructed or entirely missing (see Fig. 2C), and vice versa for unilateral right displays; even the 'diamond' configuration would only be partly rendered in unilateral displays. Thus, perceptual grouping in these variants of the target displays is much weaker (or completely absent), and it therefore does not make sense to interpret grouping-related performance in these (partly) incomplete groupings.

2.3. *Procedure*

Each trial started with the presentation of a fixation cross at the center of the screen for 1000 ms. This was followed by a pre-mask display which presented four complete disks in a diamond arrangement around fixation for 2000 ms. Next, the target display presented one of the four possible object configurations (see some examples of bilateral and unilateral left target displays in Fig. 2B and C, respectively; the full set of all possible stimuli is provided in the Supplement). In the target display, segments were removed from the top and the bottom and from either the left side, the right side, both sides, or from neither left nor right side (see Fig. 2A). Thus, zero to two segments were removed from the left and right circles and these served as the to-be-detected *targets*, whereas the two segments on the top and bottom were response-irrelevant *distractors*. Exposure times of the target display were adjusted individually for each observer based on the results of a pre-test (see details below). Finally, a post-mask display again presented four complete circles until the patient gave a verbal response to indicate on which side(s) a segment was removed from the target display (four alternatives: left, right, both, or none). The experimenter recorded the answers via keyboard press. Each trial was separated from the next by a blank screen with the central fixation cross, which was shown for 1000 ms. Fig. 2A presents an example trial sequence and the possible target displays, illustrating where the cutoff segments could be removed from a given configuration.

Prior to the experiment proper, each patient completed a pre-test that was comparable to the procedure used in previous studies (e.g., Conci et al., 2018). The aim of this pre-test was to determine the individual target display duration at which unilateral left targets could be detected with an accuracy of approximately 75%. The pre-test also served as a practice run to ensure that the instructions were fully understood. The display sequence in the pre-test was identical to the actual experiment, except that only ungrouped configurations were presented. The duration of the target display was determined using an adaptive staircase procedure with a starting duration of 200 ms, which was adjusted individually until the performance criterion (~75% correct detection of unilateral left targets) was reached. Presentation durations were estimated on the basis of 20 randomized trials (with 10, 5, 3, and 2 trials presenting unilateral left, unilateral right, bilateral, and catch-trial target displays, respectively). The unilateral left target displays were used to estimate the presentation duration of the displays in the main experiment. The mean presentation duration derived from this pretest was 731.5 ms (individual values for each patient are listed in Table 1), which is roughly comparable to a previous, related study (Conci et al., 2018).

The experiment itself consisted of 288 experimental trials, which were presented in eight blocks of 36 trials each, with a break after each block. The length of these breaks was determined by the patients themselves. Each block consisted of 8 unilateral left, 8 unilateral right, 16 bilateral, and 4 catch trials, which were presented in a randomized order. The various types of object configuration (ungrouped, left triangle, right triangle, or diamond) were presented in randomized order across the whole experiment. In summary, the experiment varied two factors, object configuration (ungrouped, left triangle, right triangle, or diamond) and target (unilateral left, unilateral right, bilateral, catch).

3. Results

3.1. *Detection accuracies*

Statistical analyses were performed using repeated-measures analyses of variance (ANOVAs) and subsequent post-hoc tests (paired-samples *t*-tests with Holm correction for multiple comparisons) with the program R Studio (RStudio Team, 2015). Our analysis approach was three-staged. An initial analysis was performed to provide an overview of the basic level of performance for the various types of configuration in unilateral right target displays, that is, displays with a single target presented in the intact (attended) hemifield. Next, we compared the various configurations in catch trials (i.e., trials without targets but with varying distractors), in order to gauge the level of guessing on the target trials. Third, of major theoretical interest, we quantified performance in the impaired, left hemispace in order to examine for object integration under conditions of inattention. This latter analysis of the left hemispace involved several comparisons that compared the various object configurations in unilateral left and bilateral target displays.

First, performance for unilateral targets in the right, unimpaired hemispace turned out very accurate overall (89.9% correct 'right' detections). A repeated-measures ANOVA of the mean detection accuracies for unilateral right targets, with the single factor object configuration (ungrouped, left triangle, right triangle, diamond), yielded a significant main effect, $F(3, 30) = 4.07$, $p = .015$, $\eta 2 = .19$ (see Fig. 4A). Holm *post-hoc* tests, however, failed to revealed any significant differences among the various configurations (ungrouped: 92.6%, left triangle: 87.4%, right triangle: 97.2%, diamond: 82.2%), all t (10)'s < 2.92, all p's > .05. This is likely owing to the familywise error correction for multiple comparisons that we used: without Holm correction, the diamond configuration depicted a less accurate performance compared to the ungrouped and right triangle configurations, both t (10)'s > 2.46, both p's < .05 (see Fig. 4A). The somewhat elevated error rates with the diamond configuration might have occurred because the patients tended to respond to the incomplete (unilateral right) diamond as if it were complete, that is, as if there was a target not only on the right but also the left side.

Second, the overall performance on catch trials showed that the participants' accuracy was also high for displays that did not contain a target (88.8% correct 'none' responses). An ANOVA of catch-trial performance comparable to that above also revealed a significant main effect of object configuration, $F(3, 30) = 4.18$, $p = .013$, $\eta 2 = .11$. However, again, Holm post-hoc comparisons failed to reveal any significant differences among the various configurations (ungrouped: 88.6%, left triangle: 88%, right triangle: 80.7%, diamond: 97.7%), all t (10)'s < 2.78, all p's > .05. Without such a familywise error correction, performance was significantly more accurate with the diamond configuration compared to the other three configurations, all t (10)'s > 2.39, all p's < .05 – suggesting that the symmetric distractors at the top and bottom of the diamond configuration facilitated responding "none" to some extent (see example stimuli in the Supplement). Overall, though, the catch-trial accuracies show that participants were able to perform the task without any indication of undue guessing responses.

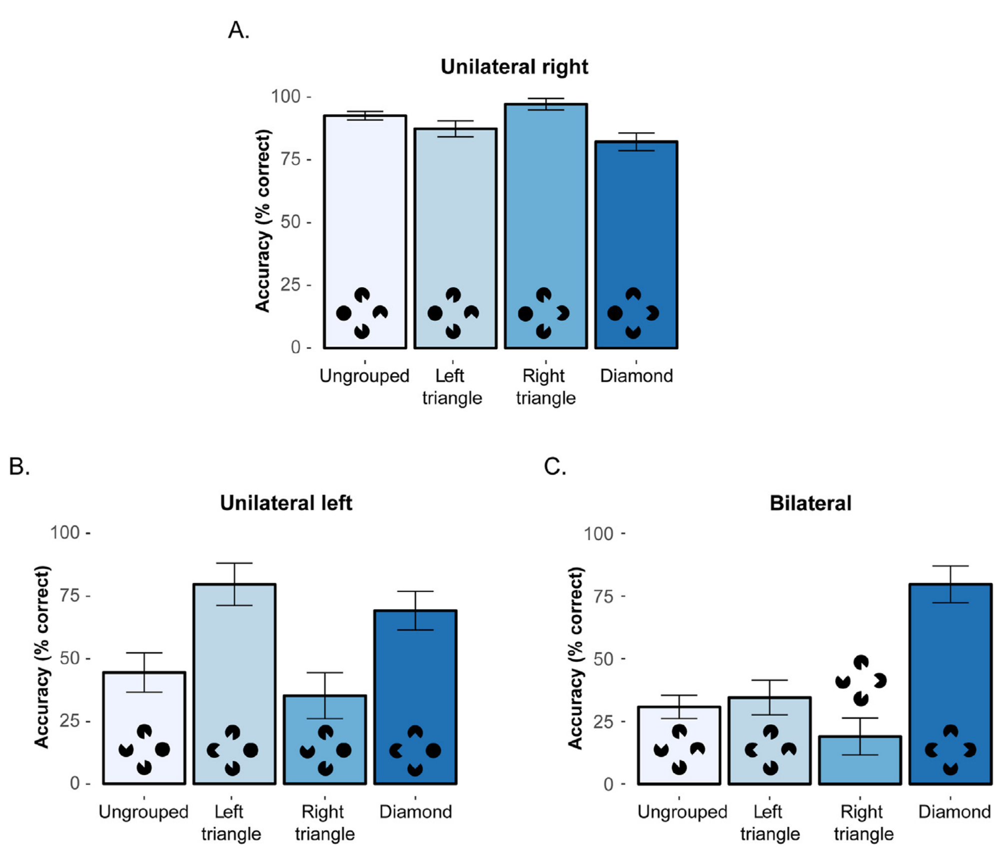


Fig. 4 – Mean percentages of correct detections (and associated within-subject 95% confidence intervals) as a function of object configuration (ungrouped, left triangle, right triangle, diamond) for (A) unilateral right target displays, (B) unilateral left target displays, and (C) bilateral target displays.

Following these preliminary analyses, we assessed performance for the impaired hemispace by computing a repeated-measures ANOVA on the detection accuracies with the factors target (unilateral left, bilateral) and object configuration.[2] The corresponding mean accuracies per condition are depicted in Fig. 4B and C. This analysis revealed a significant (Greenhouse-Geisser corrected) main effect of object configuration, F (1.47, 14.7) = 38.30, $p < .001$, $\eta2 = .44$, with performance varying overall for the various object types (ungrouped: 37.6%, left triangle: 57.1%, right triangle: 27.1%, diamond: 74.4%). While there was no significant main effect of target, F (1, 10) = 4.11, $p = .701$, importantly, the 2-way interaction was significant, F (3, 30) = 15.77, $p < .001$, $\eta2 = .19$.

To decompose the interaction, follow-up analyses were performed separately for the two types of target. First, for unilateral left targets (mean correct detections: 57.1%), the main effect of object configuration was significant, F (3, 30) = 17.97, $p < .001$, $\eta2 = .36$ (see Fig. 4B). Holm *post-hoc* tests revealed detection accuracies to be significantly higher for the left triangle (79.6%) and diamond (69.1%) configurations as compared to the right triangle (35.2%) and ungrouped (44.4%) configurations, all t (10)'s > 3.34, all p's < .023. Detection accuracies were comparable both between diamond and left triangle configurations, t (10) = 1.92, $p = .168$, and between right triangle and ungrouped configurations, t (10) = 1.52, $p = .168$. Together, this pattern of results indicates that with unilateral left displays, the emergence of a salient object grouping in the left hemifield (in left triangle and diamond configurations) substantially facilitated the rate of target detection.

Second, for the various bilateral target conditions, that is, displays that would typically lead to a pattern of extinction (Fig. 4C; mean correct detections: 41%), again, the main effect of object configuration was significant, F (3, 30) = 45.73, $p < .001$, $\eta2 = .67$. Holm *post-hoc* tests revealed accuracy to be higher for the diamond configuration (79.7%) compared to all other configurations (left triangle: 34.5%, t (10) = −8.05; right triangle: 19.0%, t (10) = −9.22; ungrouped: 30.8%, t (10) = −9.28; all p's < .001), whereas there were no differences among the latter (all $p > .05$). This pattern indicates that with bilateral displays, a given grouped object reduces extinction effectively only when the respective to-be-completed parts extend across both the impaired and the attended hemispaces (i.e., in the diamond configuration). By contrast, salient groupings that are confined to the impaired hemispace (i.e., the left triangle configuration) fail to produce a comparable increase in performance for detecting bilateral cut-off segments.

In a further analysis, we directly compared the detection accuracies for the various object configurations between unilateral left and bilateral displays, in order to determine particular configurations that depend on the availability of attentional resources. *Post-hoc* comparisons showed that the accuracies did not differ significantly between unilateral left and bilateral displays for ungrouped (44.5% vs. 30.8%), right triangle (35.2% vs. 19.0%), and diamond (69.1% vs. 79.7%) configurations (all t (10)'s < 2.87, all p's > .05). Thus, in both unilateral left and bilateral displays, the left target could be detected quite accurately when a salient grouping was presented in the entire visual field (in the diamond configuration). Conversely, with both unilateral left and bilateral displays, performance was relatively inaccurate when there was no grouping (in the ungrouped configuration), or when there was a grouping that was confined to the intact (right) hemispace (in the right triangle configuration). However, only in the case of the left triangle configuration did participants detect the left target significantly better when it was presented in unilateral left displays (79.6%) as compared to bilateral displays (35.5%), t (10) = 4.51, $p = .021$. This means there is a reliable accuracy benefit for grouped objects in the impaired, unattended hemispace, provided that the grouped object is presented unilaterally. But the benefit deriving from grouping is abolished when attention is unavailable, that is, when another (non-grouping) target needs to be processed in the intact, attended hemispace.

Of note, participants only achieved 44.5% correct responses for the ungrouped configuration in unilateral left target displays, even though prior to the formal experiment (in the pretest), we ensured that unilateral left targets could be detected with an accuracy of approximately 75% (see Methods section). This drop of performance from the pretest to the actual experiment was somewhat unexpected, given that previous studies employing a comparable procedure reported a relatively high level of performance throughout the entire experiment (Mattingley et al., 1997; Conci et al., 2009, 2018). A potential explanation for this decline in accuracy might relate to the increase in task difficulty in the current experiment. For instance, the diamond-shaped layout of the search display not only presented lateral targets, but also target-similar (yet task-irrelevant) distractors at the top and bottom disk locations in each object configuration (see Fig. 2A). Presenting these additional distractors in the display might have harmed processing of the target items in particular in our extinction patients who, by definition, have problems in detecting a target among multiple other stimuli. Moreover, unlike previous comparable studies, the current experiment did not present the various configurations in separate blocks, but in randomized order across trials, thus making it more difficult for the patients to prepare for a given, specific display. Together, these two changes in the paradigm might explain the observed reduction in performance as the experiment progressed, and this increase in difficulty might in turn explain why contralesional groupings (in the left display half) modulated response accuracy even though there was no ipsilesional stimulus that would have led to extinction behavior.

3.2. *Types of response errors*

A final analysis was performed to quantify the specific types of response errors that were made for the various object configurations in displays with a target in the impaired, left hemispace (in unilateral left and bilateral target displays).

[2] It should be noted that previous studies (e.g., Mattingley et al., 1997) sometimes computed "left detections" to quantify performance in particular in the impaired hemispace. Here, we instead quantified the overall mean detection accuracies (which would, in bilateral displays, only count the detection of both the left and right hemifield target as a correct response). However, analogous analyses performed on such a 'left detection' measure in the current experiment revealed exactly the same pattern of results as reported here for the overall (% correct) accuracy data.

That is, we systematically analyzed the distribution of errors across the various possible incorrect responses for a given target display, in order to determine–in addition to the above analyses–which specific response was predominant for a given type of configuration. First, error probabilities for unilateral left targets were analyzed using a repeated-measures ANOVA with the factor response (right, both, none) and object configuration (ungrouped, left triangle, right triangle, diamond). Note that the correct response to unilateral left displays would be "left", hence the three analyzed response alternatives were all incorrect. This analysis revealed a significant main effect of response, F (1.04, 10.4) = 15.20, $p < .001$, $\eta2 = .42$: while the participants produced only few false alarms in erroneously reporting a right visual field target (erroneous response "right": 5.8%, "both": 2.6%), they were much more likely to miss the left visual field target (response "none": 33.4%). In addition, there was also a significant effect of object configuration, F (3, 30) = 17.04, $p < .001$, $\eta2 = .11$, which essentially mirrored the above-reported result, namely, overall more errors for right triangle (21%) and ungrouped (17.8%) configurations than for left triangle (6.8%) and diamond (10%) configurations. Importantly, the 2-way interaction turned out to be significant, too, F (2.20, 22.02) = 5.91, $p = .007$, $\eta2 = .14$.

To disentangle the significant interaction (see Fig. 5A), follow-on analyses were performed separately for the three types of error responses and for each configuration. First, for the (erroneous) response "right", pairwise comparisons revealed no significant difference across ungrouped, left triangle, right triangle, and diamond configurations (all t (10)'s < 2.00, all p's > .05). There were also no differences for the (erroneous) response "both" (all t (10)'s < 1.64, p's > .05). For "none" responses, by contrast, the error probability was significantly higher for ungrouped (49.4%) and right triangle (44.3%) configurations as compared to left triangle (18.2%) and diamond (21.6%) configurations (all t (10)'s > 3.07, all p's < .035); between the former two and the latter two configurations, the error rates were comparable (all t (10)'s < 1.27, all p's > .05). This pattern shows that in unilateral left target displays, participants were better in detecting the target if it was part of a salient object grouping (in left triangle and diamond configurations) – thus mirroring the results as reported above for the detection accuracies.

Second, for bilateral target displays, the error probabilities were again analyzed by a repeated-measures ANOVA with the factors (erroneous) response (left, right, none) and object configuration. This analysis yielded significant main effects of response, F (1.22, 12.16) = 47.40, $p < .001$, $\eta2 = .70$, and object configuration, F (3, 30) = 41.01, $p < .001$, $\eta2 = .24$. The response effect confirmed that the patients indeed suffered from visual extinction, since the predominant error response for all bilateral displays was "right", (erroneous response "right": 46.8%, "left": 8.9%, "none": 1.6%; all t (10)'s > 2.98, all p's < .001; "right" responses were more frequent than "left" or "none" responses). The effect of object configuration again reflected the finding (already seen above) of errors being reduced overall only for the (fully grouped) diamond configuration (6.7%), but not for the other three types of configuration (ungrouped: 22.5%, left triangle: 21.1%, right triangle: 25.9%). In addition to the two main effects, the interaction was also again significant, F (2.23, 22.32) = 18.86, $p < .001$, $\eta2 = .36$.

Decomposing this interaction (see Fig. 5B) by pairwise comparisons showed that erroneous "left" and "none" responses were relatively infrequent and not statistically different across all four configurations, all t (10)'s < 2.55, all p's > .05. However, erroneous "right" responses (which, with bilateral target displays, reflect typical extinction behavior) occurred significantly more often with right triangle configurations (71.3%) than with ungrouped configurations (55.9%), t (10) = 3.12, $p = .022$. Erroneous "right" responses again also occurred more often than with left triangle configurations (44.9%), t (10) = −2.32, $p = .043$. Finally, the diamond configurations (15.1%) elicited relatively few erroneous "right" responses compared to each of the other three configurations, all t (10)'s > 6.12, all p's < .001. This gradual variation of performance essentially shows that the benefit of grouping is

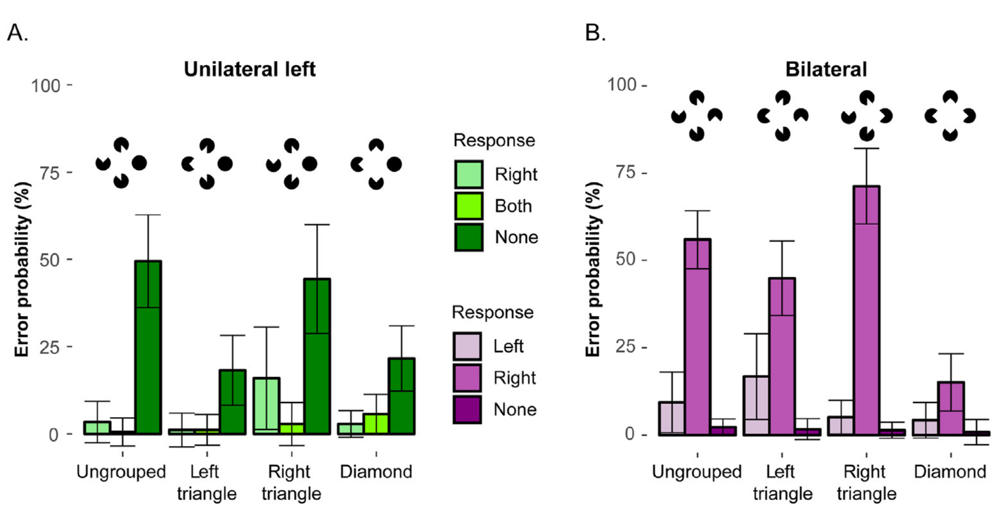


Fig. 5 – Types of response errors (and associated within-subject 95% confidence intervals) as a function of object configuration (ungrouped, left triangle, right triangle, diamond) for (A) unilateral left target displays and (B) bilateral target displays.

linked to the availability of attentional resources: the presence of a grouping that links both hemifields (diamond configuration) is most effective in reducing extinction, whereas a salient grouping that is, however, confined to the unattended hemispace (left triangle configuration) can ameliorate extinction only to a certain extent (relative to the ungrouped configurations). However, when the salient grouping is confined to the attended hemispace (right triangle grouping), then the non-salient target in the unattended hemispace is rather unlikely to be detected. This shows that the effectiveness of the grouping to capture attention depends on the availability of attentional resources in the first place.

4. Discussion

The present study investigated how perceptual grouping interacts with the allocation of selective attention. To this end, we compared object integration processes in the attended and in the unattended (i.e., impaired) hemispace of neglect patients with right-hemispheric, parietal brain lesions and associated inattention towards stimuli in the left visual hemifield. Importantly, limiting perceptual grouping operations to only one hemifield prevented the cross-hemispheric spreading of attention, which might have occurred concurrently with the integration of a grouped object. In our experiment, the patients were asked to detect lateral targets while the presented display items systematically varied in terms of grouping such that individual parts could be integrated into coherent Kanizsa-type illusory figures within the left, within the right, or across both visual hemifields. Thus, this setup permitted preattentive grouping to be disentangled from a spreading of attention into the impaired hemispace along the grouped object. Given this, our design allowed us to determine whether (i) attention is required in the first place to bind fragmentary parts into a coherent whole, and (ii) whether the formation of an integrated object can in turn act like a saliency signal that summons attentional resources.

The results showed that when individual segments were not grouped across both hemifields, detection of bilateral targets was compromised: the patients missed a high proportion of targets on the left side, which is a tell-tale sign of extinction. By contrast, when target segments were grouped to form a single coherent diamond shape, performance improved substantially (by ~49%); that is, targets on the left side were detected more frequently, showing that the completion of a coherent object reduces extinction in the impaired hemispace (consistent with Mattingley et al., 1997, and Conci et al., 2009). Similar findings of preserved access to complete objects despite severe inattention in one half of the display have previously been taken to support the view that attention is essentially object-based, that is, the integration of parts into whole objects precedes the allocation of attention (see Driver & Baylis, 1998; Humphreys, 2016; Scholl, 2001, for reviews). Attentional spreading within the boundaries of the grouped (diamond) object could then explain why the two, left- and right side targets are detected more efficiently compared to when the two targets are presented at the same lateral positions, but not within a single, integrated object (e.g., in ungrouped displays). In the latter case, attentional spreading would not be promoted by the presented structure of object elements (see Egly, Driver, & Rafal, 1994; and Chen, 2012, for a review of findings from object-based attention).

Critically, however, our results also show that a substantial reduction of extinction in bilateral displays by means of grouping was observed *only* when the object extended across both hemifields (allowing for attentional spreading to occur). In particular, completion of a salient triangle configuration within the impaired, unattended hemispace facilitated detection of a left-sided target in bilateral configurations only to a small extent. That is, processing of a task-relevant but non-salient single target item in the intact visual hemispace did hamper target detection in the impaired, unattended hemispace—despite the left side of the display consisting of a salient illusory figure. Of note, such salient object groupings have previously been found to capture attention in healthy participants (see e.g., Kimchi et al., 2016; Rauschenberger & Yantis, 2001; Senkowski et al., 2005; Wiegand et al., 2015), that is: the groupings (formed at preattentive coding stages) were interpreted as giving rise to bottom-up saliency signals that summon attention even when task-irrelevant. However, this interpretation would be inconsistent with the present results in neglect patients, which show that grouped objects do not capture attention when attention is currently engaged elsewhere.

Importantly, our design allowed more experimental control over the exact size of the unilateral Kanizsa figure compared to the previous studies of Conci et al. (2009; 2018). With their displays, the partial groupings from one hemifield were assumed to propagate into the other hemifield (see Fig. 1 for example configurations). While this is so phenomenally, how far the surface covered by the illusory object did extend into the other hemifield might have been quite variable since the spatial distribution of extinction/neglect is relative rather than absolute (e.g., Bays et al., 2010). In the current design, by contrast, the (unilateral) triangle's vertical border was delineated by the boundary induced by the cut-out sections of the upper and lower disks on the central midline—so that the illusory object was confined to only one hemifield, without extending into the other hemifield. Our results thus add support to the proposal that a grouped object reduces extinction effectively only when the respective to-be-completed parts extend across both the impaired and the attended hemispace (Conci et al., 2018). Consistent with these findings from extinction patients, studies that presented near-threshold stimulus configurations in masked-priming paradigms (Schwarzkopf & Rees, 2011) or that presented groupings under conditions of inattentional blindness (Mack, Tang, Tuma, Kahn, & Rock, 1992) have also suggested that attention plays a crucial role for successful perceptual grouping.

In unilateral left displays, we found that left-sided targets were detected significantly better when the cut-out sections were arranged such that an illusory figure could emerge within the left visual hemifield, compared to when the left display half contained an ungrouped element arrangement. That is, the patients still tended to miss the left-sided target more often in ungrouped and right triangle configurations than in diamond and left triangle configurations. Thus, patients with visual hemi-neglect seem to be able to group separate parts into coherent whole objects even when presented in the left, unattended hemispace. This process, however, is foiled whenever a second, task-relevant target is presented in the attended hemispace. The lack of a task-relevant target in the attended visual field therefore allows attentional resources to reorient from the attended, right hemispace into the neglected, left hemispace. Such reorienting of attention in turn triggers completion of the shape (e.g., in left triangle or diamond configurations), with the integrated shape in turn increasing the saliency of the left-sided target, thereby enhancing its detectability. This shows that neglect is ameliorated by salient object groupings—but, importantly, this benefit is conferred only when attention is available. In general agreement with this finding, previous studies have reported that grouping can increase the conspicuity of a Kanizsa-type target, thereby enhancing search efficiency (Conci, Müller & Elliot, 2007; Conci, Töllner, Leszczynski, & Müller, 2011; Nie, Maurer, Müller, & Conci, 2016; Wiegand et al., 2015).

In summary, our results further support the idea that attention is necessary for successful object integration (e.g., Conci et al., 2018). Accordingly, guidance of attention by grouped objects is not possible without attending to the to-be-grouped objects in the first place. This result pattern may, for instance, be explained within the framework of the reverse hierarchy theory (Hochstein & Ahissar, 2002). In this view, the individual inducer elements (the circles with missing segments) would undergo some basic, "preattentive" processing in an initial feedforward sweep of processing. Selective attention is in turn engaged subsequently and triggers perceptual grouping via recurrent feedback from higher to lower levels of processing in the visual hierarchy. That is, an integrated object could guide attention only after some attention-dependent grouping has generated a complete-object representation. This implies that object completion can be successful when sufficient attentional resources are deployed to those parts of the visual field that could give rise to the perception of an integrated object, but not when the allocation of attention towards these grouping-inducing elements is prevented (e.g., by a task-relevant target that is presented elsewhere). Overall, this suggests that attention may indeed act like a "glue" to bind parts into wholes (Conci et al., 2018), contrary to the predominant view advocated in several of the above-mentioned studies. The attention-dependent integration of image elements has previously been referred to in terms of "incremental grouping" (Roelfsema, 2006; Roelfsema & Houtkamp, 2011), which appears to reflect a time-consuming and capacity-limited process that requires the gradual spread of attention across the representation of an object. This spreading along the boundaries of an object would in turn establish an object-based representation that is available for higher-order processing.

Author contributions

LN collected data, analyzed data, and wrote the paper. KF designed the experiment and critically revised the manuscript. ALB collected data and critically revised the manuscript. IG recruited participants, examined medical records, confirmed diagnostic status of participants, and created the lesion mapping figure. HJM critically revised the manuscript. MC designed the experiment, supervised data collection, wrote and critically revised the manuscript. All authors read and approved the final manuscript.

Open practices

We report how we determined our sample size, all data exclusions, all inclusion/exclusion criteria, whether inclusion/exclusion criteria were established prior to data analysis, all manipulations, and all measures in this study. No part of the study procedures or analyses were pre-registered prior to the research being conducted. However, all relevant study materials, data, and analysis code are available on the Open Science Framework following this link: https://osf.io/thba7/.

The study in this article earned Open Materials and Open Data badges for transparent practices. Materials and data for the study are available at https://osf.io/thba7/?view_only=3df9262964034997821040bfd1fe7294.

Declaration of competing interest

The authors declare that they have no competing interests.

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Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cortex.2021.02.011.

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Supplement

Nowack, L., Finke, K., Biel, A. L., Keller, I., Müller, H. J., & Conci, M. (2021). Attention capture by salient object groupings in the neglected visual field. *Cortex*

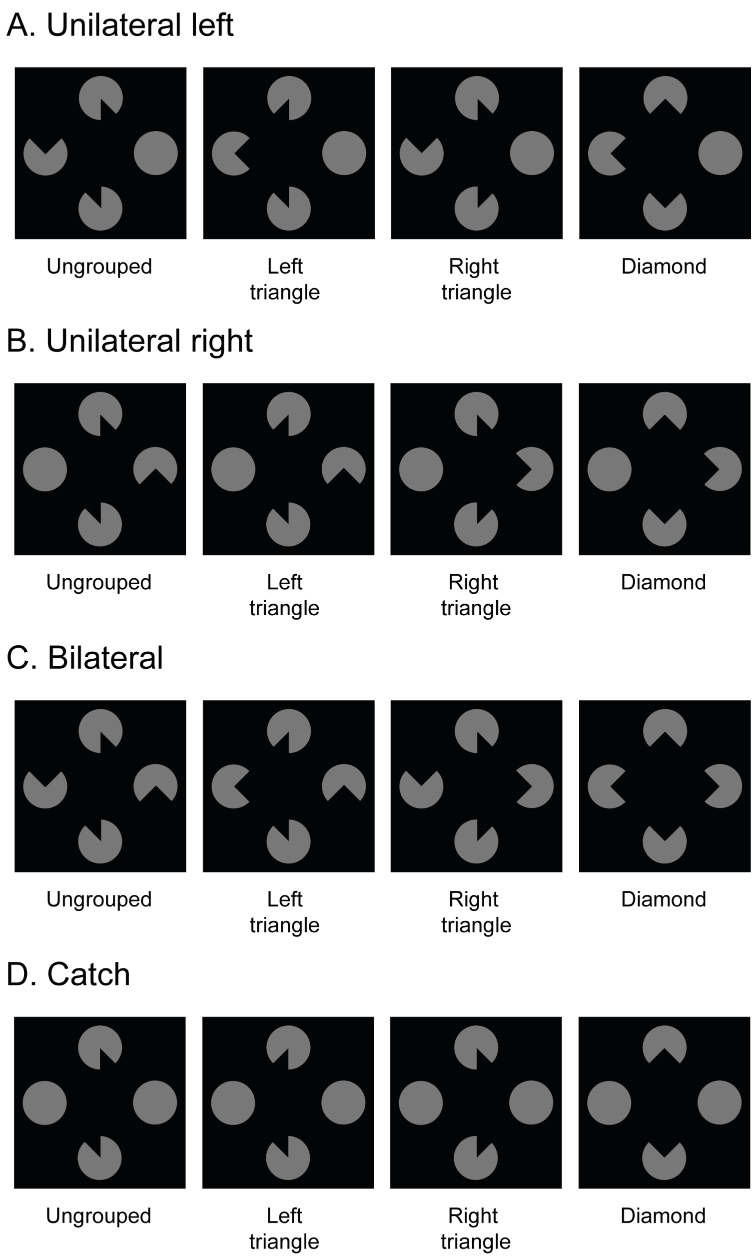

Figure S1. Examples of the different types of object groupings presented in (A) unilateral left, (B) unilateral right, (C) bilateral, and (D) catch target displays.