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Simultanagnosia and object individuation

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ABSTRACT

Simultanagnostic patients have difficulty in perceiving multiple objects when presented simultaneously. In this review article, I discuss how neuropsychological research on simultanagnosia has been inspirational for two interconnected lines of research related to the core mechanisms by which the visual system processes cluttered scenes. First, I review previous studies on enumeration tasks indicating that, despite their inability to identify multiple objects, simultanagnosic patients can enumerate up to 2–3 elements as efficiently as healthy individuals (the so-called “subitizing” phenomenon). This intriguing observation is one of the first results to support the existence of an “object individuation” mechanism that can spatially tag a limited set of objects simultaneously, and resonates with recent research on the brain dynamics of enumeration in healthy individuals. Second, I further develop the implications of the dissociation between object identification and object enumeration in simultanagnosia specifically for the distinction between object identification and individuation. The latter distinction has been the subject of recent neuroimaging research that has provided fine-grained information on the spatial as well as temporal aspects of object individuation and recognition. The lessons learned from neuropsychological research on exact enumeration in simultanagnosia can be generalized to the normal functioning of the human mind, and have provided insightful clues for cognitive neuroscience.

Simultanagnosia and multiple object processing

In this review, I will discuss how research on enumeration in simultanagnosia has helped redefine our understanding of multiple object perception in the subitizing phenomenon, as well as delineate a hierarchy in object coding, with a distinction between multiple object individuation and identification. These results have improved our knowledge of how the visual system processes cluttered scenes.

Damage to the posterior cortex is associated with a variety of deficits in visuospatial processing (Behrmann, Geng, & Shomstein, 2004; Humphreys, 1998; Riddoch et al., 2010), which often include simultanagnosia. Simultanagnosia is the inability to perceive more than one object at a time (Robertson, 2014) and is a typical symptom of Balint’s syndrome (Bálint, 1995; Husain & Stein, 1988). The most likely locus of the lesion causing this deficit lies in bilateral parietal areas (see Riddoch et al., 2010), but some patients also show lesions in extrastriate areas (e.g., Levine & Calvano, 1978; see Farah, 1990, for a distinction between two forms of simultanagnosia).

There is a mixture of symptoms that accompany patients with simultanagnosia. However, the most striking and consistent symptom is a failure in simultaneous processing of multiple elements (Rizzo & Vecera, 2002; Robertson, 2014). The failure is observed in different contexts. For instance, the patients are incapable of describing complex scenes, and typically mention only disconnected events (e.g., Kinsbourne & Warrington, 1962). In simple perceptual tasks, they often miss the presence of a specific element (e.g., a curve segment) when multiple segments are presented in the visual fields (e.g., Robertson & Treisman, 2006). However, if the same items are grouped into a single perceptual unit (and the crucial element becomes part of that unit), the patients’ accuracy improves greatly, in line with the idea that single object perception is (relatively) preserved in simultanagnosia.

What process is specifically damaged in simultanagnosic patients? Is multiple object processing
impaired tout court, or are there mechanisms that remain relatively intact in simultanagnosia? Several proposals have been made about the nature of simultanagnosia. According to some investigators (Duncan et al., 2003), simultanagnosia is merely a deficit in visual processing speed. This interpretation stems from some early reports (Balint, 1909, 1995; Luria, 1959) of slow processing even in the case of single items in simultanagnosic patients. The account in terms of slowing has been substantiated by recent evidence (Duncan et al., 2003; Neitzel et al., 2016) based on the mathematical formalization of the various subcomponents of multiple object processing (Bundesen, 1990) indicating that processing speed is the component mainly affected in simultanagnosia.

In contrast, some investigators argue that simultanagnosia could be better understood as a deficit in matching the identity of an object with the specific location occupied by the object in the visual field (Coslett & Saffran, 1991; Dehaene & Cohen, 1994). This account strongly evokes the idea of “object-file”, a metaphor used in developmental and adult research to explain the process of object recognition (Kahneman, Treisman, & Gibbs, 1992; Leslie, Xu, Tremoulet, & Scholl, 1998; Spelke, Kestenbaum, Simons, & Wein, 1995). According to the “object-file” metaphor, object processing is a multifaceted process that entails the accumulation of object features and the integration of the ensemble of features with the information on the spatial location occupied by the set of features in the visual field. Here I use the terms “object individuation” to indicate the stage where the object file is initialized, and “object identification” to refer to the finalization of the object file. While some initial features (e.g., colour) may be coded and integrated with a distinct location already during object individuation, it is only at the object identification level that all object features are fully integrated with the spatial location in the visual field (see Leslie et al., 1998; Xu & Chun, 2009). Object identification requires matching the current input with a stored representation of visual objects, and this matching likely involves maintenance of the current input in working memory while a matching process is carried out.

Some researchers have proposed that simultanagnosia reflects a deficit in multiple object processing already located at the object individuation stage (Laeng, 1999), while object identification would be relatively spared (Coslett & Saffran, 1991; but see Coslett & Lie, 2008). However, as I describe in this review article, the findings from enumeration tasks (Dehaene & Cohen, 1994; Demeyere, Lestou, & Humphreys, 2010; Lemer, Dehaene, Spelke, & Cohen, 2003) challenge this view, by pointing to efficient enumeration of (a limited number of) multiple items in such patients. What does enumeration in simultanagnosia tell us about multiple object processing and visual perception in general? First, results on enumeration in simultanagnosia show that multiple object processing is not completely damaged in these patients. More specifically, they point to the existence of an individuation system that allows for a representation of the items as individual entities, a type of representation that is appropriate for enumeration. Second, the fact that simultanagnosia is not due to a failure in object individuation further suggests the existence of multiple stages in multiple object processing, and that the processes of object individuation and identification are separable.

**Enumeration, subitizing, and individuation**

Several studies on numerosity computation (Dehaene, 1997; Mandler & Shebo, 1982) have delineated a distinction between estimation—namely, a procedure that ensures an approximate representation of object numerosity—and exact enumeration. Exact enumeration relies on the precise representation of the number of objects in the visual field and is the result of a process that considers each element to be enumerated only once (Trick & Pylyshyn, 1994). This is due to the fact that items need to be represented individually in order to be enumerated correctly, although they do not need to be fully identified (e.g., whether there are three candies or three books is irrelevant for coding their numerosity).

The hallmark of exact enumeration is the subitizing effect—namely, the fast and accurate enumeration of a small set of elements as compared to slower and/or less accurate enumeration (“counting”) for larger sets of elements (Mandler & Shebo, 1982, Figure 1(A)). More precisely, when enumeration is studied with long (or unlimited) stimulus presentation, participants enumerate small numerosities efficiently (the “subitizing” phenomenon) and (slowly but precisely) count the larger numerosities. When brief stimulus presentation is used, subitizing is still visible for small
numerosity. However, counting is no longer possible, and individuals try to estimate the numerosity of the larger set. According to early proposals (Pylyshyn, 2001; Trick & Pylyshyn, 1993), subitizing reflects the operation of a pre-attentive mechanism of individuation, which allows for a spatial tagging of approximately 3–4 elements simultaneously. However, there is growing consensus that individuation is one of the key functions of attention (Cavanagh, 2011), and that subitizing reflects the functioning of a capacity-limited, attention-based mechanism that enables the simultaneous individuation of a maximum of 3–4 elements (Demeyere, Rotshtein, & Humphreys, 2012; Vetter, Butterworth, & Bahrami, 2008). As I describe below, findings on enumeration in simultanagnosia represent one of the first pieces of evidence in favour of a link between subitizing and (attentive) individuation.

**Simultanagnosia, subitizing, and individuation**

Although there are a limited number of investigations on enumeration in simultanagnosia, all the studies have consistently reported that despite their inability...
to identify multiple objects simultaneously, simultanagnosic patients can efficiently enumerate small sets of objects presented simultaneously, and show the subitizing effect (up to 3 elements, see Dehaene & Cohen, 1994).

The first evidence of a preserved subitizing effect in simultanagnosia was reported by Dehaene and Cohen (1994). They tested five patients with damage to parietal, occipital, and temporal areas, who all presented symptoms of simultanagnosia. In an enumeration task with a varying number of simple geometrical shapes (1–6 dots), patients could process accurately up to 2–3 elements, with abnormally impaired performance for the counting range. Consistent with this finding, Demeyere and colleagues (Demeyere et al., 2010) described a single case, M.H., who had extensive damage to posterior parietal areas and a deficit in multiple object processing. M.H.’s performance in the enumeration task replicated the dissociation reported by Dehaene and Cohen (1994), with preserved ability to enumerate up to 4 objects (equivalent to both healthy and patient controls) and strongly impaired performance in the counting range relative to control individuals. In some cases, parietal lesions and simultanagnosia may lead to a normal subitizing effect in accuracy, but result in abnormal response speed (e.g., see Lemer et al., 2003).

These findings indicate that simultanagnosic patients retain some form of processing of multiple objects, and that they are able to represent them as distinct, separate elements. In other words, they can individuate multiple objects correctly. Two other results specify further the “spatial” nature of individuation. First, in line with the idea that individuation is closely linked to spatial location coding, simultanagnosic patients show improved enumeration for quantities above the subitizing range when the spatial separation between elements increases (Demeyere et al., 2010). Second, the improvement shown by some patients in enumerating numerosities when the elements are arranged in canonical, familiar arrangements (e.g., four elements arranged to form a square) suggests that distinct spatial coding of the elements is at the basis of individuation (otherwise, no difference between a triangle and a square, and therefore no difference between three and four items, would be perceived, see Dehaene & Cohen, 1994).

Overall, these results have provided several clues for the understanding of exact computation of quantities, and of subitizing in particular. The fact that the subitizing effect is relatively preserved in simultanagnosia suggests the existence of a perceptual, capacity-limited mechanism that enables the efficient individuation of small sets of objects for enumeration. This intriguing observation is complemented by recent behavioural and neuroimaging research in healthy individuals on the brain dynamics of exact enumeration.

Behavioural and neuroimaging research in healthy individuals suggests that enumeration is grounded on an attention-based mechanism that individuates relevant objects, either singly or a limited set simultaneously (for a review, Mazza & Caramazza, 2015). For instance, behavioural research has shown a substantial modulation of accuracy for small target numerosities as a function of perceptual/attentional load (Egeth, Leonard, & Palomares, 2008; Raino, Koivisto, Revonsuo, & Hannula, 2008; Vetter et al., 2008), suggesting an overlap between the mechanism underlying the generation of subitizing and attention processing (Cavanagh, 2011). The suggested overlap between attention functions and the processing of small quantities is reminiscent of the preserved efficiency found in simultanagnosia for both feature search tasks (where the target is defined by a unique property, and attention can efficiently select the target) and subitizing (Dehaene & Cohen, 1994). This parallelism invites the inference that attention-based individuation (at least for items possessing a unique feature), which allows the visual system to spatially tag either single or (a limited set of) elements, is equally efficient in healthy individuals and in simultanagnosic patients.

Support for the relationship between attention-based processes and individuation has recently come from functional magnetic resonance imaging (fMRI) studies (Ansari, Lyons, van Eimeren, & Xu, 2007; Vetter, Butterworth, & Bahrami, 2011), which have indicated the selective involvement of brain structures typically linked to stimulus-driven attention (such as the temporoparietal junction, TPJ, see Corbetta & Shulman, 2002; Riddoch et al., 2010) in the processing of small versus large object numerosities. For instance, Vetter et al. (2011) manipulated both target numerosity and perceptual load, and found that subitizing efficiency correlated with both perceptual load and activity in the right TPJ. Crucially, the modulation of TPJ was visible only for small target
numerosities, thus suggesting that attention can efficiently select small sets of items (up to 3 elements approximately), and that it has a critical role in the emergence of subitizing. Patient-based investigation confirms to some extent the right lateralization in some areas of the cortex in the emergence of subitizing, together with an involvement of the left posterior occipital cortex (Demeyere et al., 2012).

Converging results also come from electroencephalography (EEG) research focusing on the brain temporal dynamics of enumeration. Recent studies (Ester, Drew, Klee, Vogel, & Awh, 2012; Mazza & Caramazza, 2011; Mazza, Pagano, & Caramazza, 2013) have investigated a mid-latency (200–300 ms post stimulus onset) neural response in posterior visual areas (N2 posterior contralateral, N2pc; Luck & Hillyard, 1994) typically observed in visual search tasks. This response was originally associated with the selective individuation of a target presented among distractors. By manipulating target numerosity during enumeration tasks, these recent studies have found that the N2pc successfully tracks the variation in target numerosity, thus further highlighting the link between attention selection and multiple object individuation.

Consistent with the fMRI findings described above, the asymptote of the modulation of this response at approximately 3–4 elements (Ester et al., 2012; Pagano & Mazza, 2012) indicates a capacity limit in simultaneous object individuation. Consistent with the fMRI findings described above, the asymptote of the modulation of this response at approximately 3–4 elements (Ester et al., 2012; Pagano & Mazza, 2012) indicates a capacity limit in simultaneous object individuation that mirrors the behavioural subitizing effect (Figure 1(B)). This latter aspect is supported by the observation that the neural asymptote of N2pc correlates with individual subitizing limits as seen from behavioural performance (Ester et al., 2012; Pagano, Lombardi, & Mazza, 2014). On the basis of these findings, we (Mazza & Caramazza, 2015; Mazza et al., 2013) have proposed that the individuation mechanism reflected in this neural response provides individual representations that are appropriate for exact enumeration.

In line with research on healthy individuals (e.g., Trick & Pylyshyn, 1994), it has been suggested that the dissociation between a retained subitizing effect and an abnormally impaired enumeration rate for large numerosities in simultanagnosia would speak in favour of the existence of two separate mechanisms for the enumeration of small (subitizing range) versus large (counting range) elements (Dehaene & Cohen, 1994; Demeyere et al., 2010). Some studies (Demeyere & Humphreys, 2007) have additionally found a dissociation between counting and estimation. For instance, the simultanagnosic patient (G.K.) tested by Demeyere and Humphreys (2007) was severely impaired in counting multiple elements (>3 elements), but not in estimation. These results provide the basis for a compelling account on the distinction between subitizing, counting, and (to some extent) estimation, an issue that has been debated for years in cognitive neuroscience (Demeyere et al., 2012).

Finally, recent research (Thomas, Kveraga, Huberle, Karnath, & Bar, 2012) has shown that low-spatial frequencies improve the ability of simultanagnosic patients to process some types of stimulus configuration, raising the question of whether intact subitizing in simultanagnosia is mediated by the processing of low-spatial frequency contents of the stimulus array. However, modulation of the frequency content in healthy subjects influences performance both in the subitizing and in the counting ranges (Simon, Peterson, Patel, & Sathian, 1998), thus suggesting that the dissociation seen in simultanagnosia between normal subitizing and impaired counting does not rely on a specific spatial frequency.

**Simultanagnosia, individuation, and identification**

The existence of subitizing in simultanagnosia indicates that simultanagnosia is not due to a failure in individuation, and invites the inference that individuation and identification are anatomically and behaviourally separable stages of object processing. As I outlined above, simultanagnosia may consist in a deficit to finalize the representation of the elements presented in the visual field. As this operation probably requires the maintenance of individual representations in a working memory buffer, the deficit may be strongly linked to disorders in visuospatial memory, and should be more evident when a representation of multiple items needs to be retained in time (Demeyere et al., 2010). Thus, the deficit might take different forms, from a radical reduction of the number of individual items available in working memory, to a decrement in terms of detailed resolution of each individual representation.

The distinction between object individuation and identification has also been drawn by various models of vision on healthy individuals (Kahneman et al., 1992; Pylyshyn, 2001), and has been the focus...
of recent neuroimaging research on healthy subjects providing fine-grained information on the spatial as well as temporal aspects of this dissociation (see Mazza & Caramazza, 2015; Xu & Chun, 2009).

First, fMRI research (Bettencourt & Xu, 2016a; Xu & Chun, 2006) has proposed the differential involvement of two parietal areas (inferior intra-parietal sulcus, IPS, and superior IPS) in object individuation and object identification, respectively. This account is supported by findings showing that the activity in the inferior IPS increases as a function of the number of relevant objects in the visual field (up to approximately 3–4 items), regardless of their complexity. In contrast, variation in the activity of the superior IPS (as well as in some extrastriate areas, such as the lateral occipital complex) correlates with object complexity rather than object numerosity. This complex modulation acts as evidence that object individuation is reflected in the activity in inferior IPS, whereas the complexity-related modulation of the activity in the superior IPS supports object identification.

Second, electrophysiological studies have provided converging evidence for a distinction between object individuation and identification, uncovering the existence of two temporally separated brain activations during the execution of visual attention tasks. The first response (N2pc) reflects a relatively early activation of posterior visual areas (including parietal and extrastriate sites, see Hopf et al., 2000) that is evoked by the presence of a relevant object in the visual field (Luck & Hillyard, 1994). The N2pc is invariant with respect to task requirements, as it is measured when participants are asked to detect, localize, and identify the target element (e.g., Mazza, Turatto, & Caramazza, 2009; Mazza, Turatto, Umiltà, & Eimer, 2007; Töllner, Conci, Rusch, & Müller, 2013). Together with the numerosity-related modulation seen in enumeration (as mentioned above) as well as other tasks (such as multiple object tracking, Drew & Vogel, 2008), this aspect suggests that N2pc reflects an attention-based individuation mechanism that forms a representation of either a single or a limited set of objects, making it available for further cognitive operations (Figure 1(B)). Finally, this response is sensitive to perceptual factors (such as grouping, see Mazza & Caramazza, 2012) but is not modulated by the numerical identity of the target elements (e.g., presenting two “3s” does not affect the N2pc; see Pagano & Mazza, 2013). Thus, in line with the findings on subitizing in simultanagnosia that indicate a dissociation between object individuation and identification, this observation corroborates the idea that object individuation is a stage that operates separately from those mechanisms involved in the semantic aspects (the processing of numerical values, in this case) of the target elements.

Finally, EEG studies in the past decade have highlighted a second sustained lateralized activity (contralateral delayed activity, CDA, 350–600 ms post stimulus, Vogel & Machizawa, 2004), which reflects activation of parietal and ventral extrastriate areas (Becke, Müller, Vellage, Schoenfeld, & Hopf, 2015) and occurs only when the task requires the relevant object/s to be encoded in greater detail. For instance, CDA is elicited only in discrimination but not in simple detection or localization tasks (Mazza et al., 2009; Mazza et al., 2007). This response is sensitive to the number of elements that need to be maintained during a memory task or in enumeration (Figure 1(B); Luria, Balaban, Awh, & Vogel, 2016, for a review). However, it is also related to encoding complexity, with more complex elements eliciting larger CDAs (Gao et al., 2009; Luria, Sessa, Gotler, Jolic, & Del-l’Acqua, 2010). Thus, this response seems to be associated with a stage where all the perceptual information about an object becomes available for the finalization of an object file, a type of representation that provides the basis for what I have referred to as “object identification”. This could represent the stage that is specifically impaired in simultanagnosic patients. In line with this hypothesis, a recent study (Stasenko, Garcea, Dombovy, & Mahon, 2014) reported the case of a patient with impaired object-colour knowledge in the absence of impairments in colour perception, thus suggesting that simultanagnosia may represent a disconnection in the ability to integrate several object features together with their corresponding location.

Overall, most of the results on simultanagnosia converge with recent neuroimaging research supporting the idea of hierarchical processing in object perception, with object individuation preceding the stage of object identification. In addition, the results converge with findings from animal studies indicating that different forms of spatial representation are present in the posterior parietal cortex (which is often the locus of simultanagnosia), which acts as a
hub in the dorsal pathway that is associated with ventral regions linked to object recognition (for a review, see Kravitz, Saleem, Baker, & Mishkin, 2011).

Conclusions

Is simultanagnosia a generalized failure in processing multiple objects? Here I have presented findings from neuropsychological research on simultanagnosia and enumeration tasks that highlight how multiple object processing is not entirely damaged in these patients. These findings are relevant for the understanding of human cognition for at least three reasons.

First, studying enumeration in simultanagnosia has provided insight into the nature of subitizing, lending support to the existence of a basic, attention-based mechanism that simultaneously initiates a representation of 3–4 elements and allows for their individuation. Data on simultanagnosic patients were among the first findings suggesting that subitizing depends on this mechanism. The dissociation between preserved subitizing and estimation versus impaired counting in these patients additionally supports the hypothesis that the three effects may rely on different mechanisms. However, it should be noted that this interpretation is based on single dissociations. Thus, the difference between enumerating small versus large quantities could rely on a quantitative difference related to task difficulty rather than two separate mechanisms (see Demeyere et al., 2010, for a discussion). For instance, enumeration in the counting range may require the iterative application of the individuation mechanism, and this re-iteration may be impaired in simultanagnosia. Future research should examine this issue in detail, especially because the mechanisms underlying exact enumeration for large quantities (in both patients and healthy individuals) have remained largely unexplored.

Second, the dissociation between intact subitizing and impaired identification suggests that simultanagnosia could represent a valid model to probe the different levels involved in object perception, especially the distinction between object individuation and identification. Future research directly using neuroimaging (for instance, EEG) measures on these patients could provide a more stringent test for the distinction between object individuation and identification (see Demeyere et al., 2012; Neitzel et al., 2016, for recent attempts).

Some findings seemingly challenge the view that object individuation is (relatively) preserved in simultanagnosia. For instance, a single-case study describes a patient with simultanagnosia who, when asked to report the location of a specific element, failed to localize it correctly (Robertson & Treisman, 2006), despite being able to detect its presence fairly well when it was part of a single entity. Another study reports the case of a patient who was severely impaired in localizing objects (in addition to an increase in illusory conjunctions—the erroneous combination of features and shapes—Friedman-Hill et al., 1995). These data are suggestive of a finer distinction among various mechanisms underlying the execution of tasks requiring multiple object processing. Thus, future research within the same patient should directly compare the performance during the execution of various tasks involving multiple object processing, such as enumeration, localization, and identification. This evaluation has been done in the case of extinction, another form of visuospatial deficit in processing multiple objects presented in the contralesional side together with an object or objects in the ipsilesional side. In line with the dissociation hypothesized above, Vuilleumier and Rafal (2000) found that patients with extinction could enumerate contralesional objects correctly, despite their inability to localize them correctly. Comparing these results with the performance of simultanagnosic patients could lead to a better understanding of the mechanisms involved in multiple object perception.

Finally, data on simultanagnosia in enumeration could be useful to study the dissociation between implicit (unconscious) and explicit (conscious) spatial processing, an area of research that has been the focus of intense investigation on healthy subjects for decades. Some investigations (Jackson, Swainson, Mort, Husain, & Jackson, 2004; Karnath, Ferber, Rorden, & Driver, 2000; Robertson, 2014; Robertson, Treisman, Friedman-Hill, & Grabowecky, 1997) have reported that patients with simultanagnosia are capable of processing the spatial location (as well as some other non-spatial features) of objects implicitly (i.e., without awareness). This dissociation could explain why exact enumeration of small object quantities (which does not require explicit location information) is preserved in these patients. More generally, dissociations between explicit and implicit object processing are typically found in other visual...
deficits, such as neglect and extinction (Driver & Mattingley, 1998). The comparison between simultanagnosia and these deficits could allow a better characterization of residual abilities in multiple object perception of the various forms of visuospatial disorders (Duncan et al., 2003; Rizzo & Vecera, 2002).

In conclusion, rather than being unique to patient-based research, the findings from neuropsychological research on exact enumeration in simultanagnosia provides useful insight on multiple object processing in the healthy human mind.

Note

1. A recent study (Bettencourt & Xu, 2016b) has indicated that inferior IPS overlaps primarily with V3A/B, and superior IPS with IPS0-2.

Disclosure statement

No potential conflict of interest was reported by the author.

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