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Visual search does not always predict performance in tasks that require finding targets among distractors: The case of line-ending illusory contours

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ABSTRACT

The standard visual search task is integral to the study of selective attention and in search tasks target present slopes are the primary index of attentional demand. However, there are times when similarities in slopes may obscure important differences between conditions. To demonstrate this point, we used the case of line-ending illusory contours, building on a study by Li, Cave, and Wolfe (2008) where orientation-based search for figures defined by line-ending illusory contours was compared to that for the corresponding real-contour controls. Consistent with Li et al. (2008), we found search to be efficient for both illusory contour figures and the corresponding real-contour controls, with no significant differences between them. However, major differences between illusory contours and the real-contour controls emerged in selective enumeration, a task where participants enumerated targets in a display of distractors, with the number of targets and distractors manipulated. When looking at the distractor slopes, the increase in RT to enumerate a *single target* as a function of the number of distractors (a direct analogue to target present trials, with identical displays), we found distractor costs for illusory contour figures to be over 100 ms/distractor higher than for the corresponding real-contour controls. Furthermore, the discrepancies in RT slope between 1–3 and 6–8 targets associated with subitizing were only seen in the real-contour controls. These results show that similarities in RT slopes in search may mask important differences between conditions that emerge in other tasks.

The attentional demands of defining perceptual properties are often investigated using the standard visual search task, a task where participants seek a specific target item among varying numbers of non-targets (distractors), hitting one key if the target is present and another if the target is absent. The distractor costs, that is, the increases in RT with each additional distractor, is measured, both when the target is present and when it is absent, though the target present slopes are given particular emphasis. Although RT slopes may vary widely (e.g., Wolfe, 1998), when target present slopes are low (shallow) search is deemed efficient, and the attentional demands are judged to be low. In contrast, when the RT slopes are higher (e.g. > 10 or 20 ms/distractor) attentional demands are deemed to be more substantial. However, when search is efficient, it is possible that a great deal of diversity may be hidden in conditions where RT slopes approach zero. In this study, we demonstrate this point building from a classic paper by Li et al. (2008) that examined line-ending illusory contours, comparing processing for illusory contours with that for the corresponding real contour controls. In our study, we compare illusory contour figures first in search, and then in other tasks that are thought to require attentional selection, namely enumeration (enumerating targets) and selective enumeration (enumerating targets among distractors). The results of this series of experiments have relevance for both search and enumeration.

In vision, it has long been known that we can sometimes see contours even when the differences in brightness and colour normally associated with contours are absent (e.g. Kanizsa, 1979; Marr, 1982). Illusory contours are lines that people see even though the viewing conditions are such that the differences in lighting or colour that typically define object boundaries are absent. These contours are important both for our ability to recognize the objects we see and interact with them, touching, catching, or dodging them. There are several types of illusory contour, but one is called the line-ending illusory contour, one where the bounding contours for the object are defined by termination points against a textured background of lines. An example is shown in Fig. 1b, where vertical bars are defined against a surface of diagonal lines. In cases such as these items are defined by discontinuities in the textured background of lines. For comparison, see Fig. 1a, where the same figures are defined by real lines (the real-contour controls).

Li et al. (2008) were interested in the attentional demands of defining line-ending illusory contours (cf. Gurnsey, Humphrey, & Kapitan,

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(a)

(b)

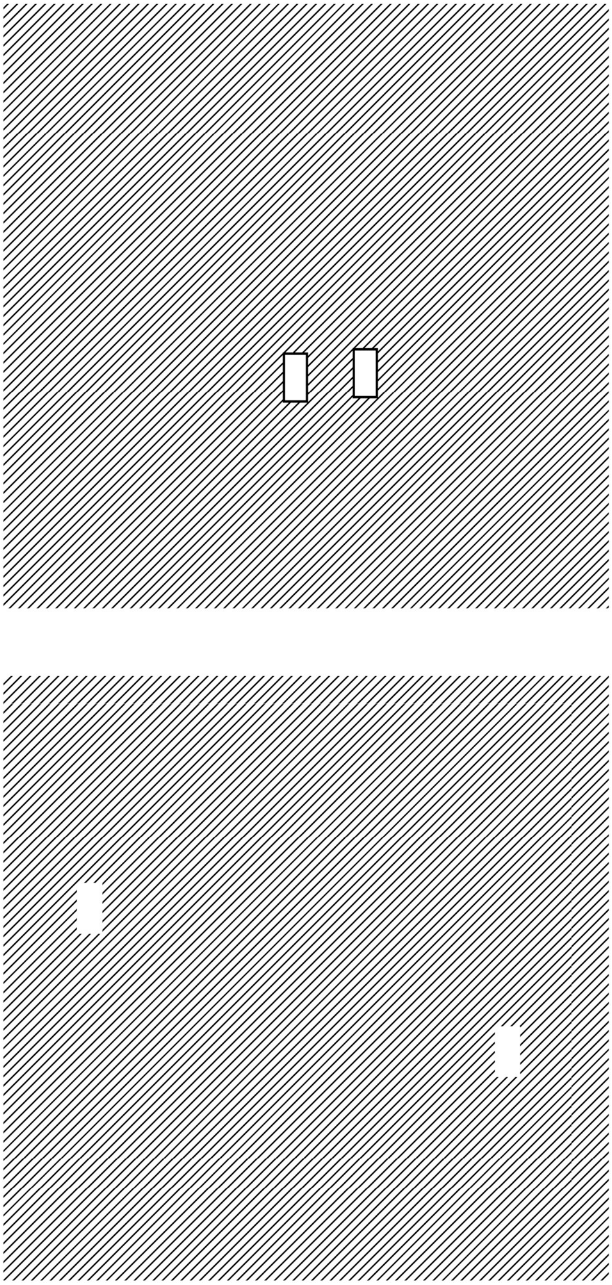


Fig. 1. Stimuli used in these studies (a) Real-contour controls (b) Line-ending illusory contour figures presented against a background grid of diagonal lines.

1992). To investigate this issue, they had participants search for targets that differed in orientation from distractors and compared performance when the items were defined by line-ending illusory contours with that for the corresponding real-contour controls. They found that target present slopes, the RT costs of each additional distractor as measured in target present trials, did not differ significantly between line-ending illusory contours and the real-contour controls. For the remainder of this document we will refer target present slopes as distractor costs for the sake of clarity. We do this because we will be discussing a number of different RT slopes, some involving increases in RT to find or enumerate a single target as a function of the number of distractors (e.g. target present slopes in search, increases in the amount of time required to enumerate a single target as a function of the number of distractors in selective enumeration) and some involving increases in RT to enumerate a target as a function of the number of targets as occurs in RT slopes in enumeration.

Thus, Li et al. (2008) found no significant differences in distractor costs between real and illusory contours, and they took that as evidence that the attentional demands of orientation based search were not appreciably larger for illusory contours than for the same items defined by actual contours (the real-contour controls). Moreover, because those distractor costs were relatively low, they concluded that the processes involved in defining line-ending illusory contours did not make extensive attentional demands, or at least not more than seeing the same items defined by lines.

In this study, we build from this example, first doing a partial replication of Li et al.'s original search study and then going on to variants of the enumeration task, a task that is also thought to make attentional demands (e.g., Burr, Turi, & Anobile, 2010; Watson, Maylor, Allen, & Bruce, 2007). Enumeration, quickly and accurately determining the number of targets in a display, is an interesting topic in its own right, and one with a long history (e.g., Hamilton, 1880; Jensen, Reese, & Reese, 1950; Jevons, 1871; Kaufman, Lord, Reese, & Volkmann, 1949; Mandler & Shebo, 1982). Although the research was initially behavioural in more recent years it has also been studied using techniques from neuroscience (e.g., Demeyere, Rotshtein, & Humphreys, 2012; Ester, Drew, Klee, Vogel, & Awh, 2012; Harvey, Klein, Petridou, & Dumoulin, 2013). Research suggests that enumeration performance is affected by attentional manipulations, and in particular those related to performance in search (e.g., Trick & Enns, 1997a, 1997b; Trick & Pylyshyn, 1993, 1994; Watson et al., 2007; Watson, Maylor, & Bruce, 2005; Watson, Maylor, & Manson, 2002). Thus, there is reason to expect that if two conditions produce comparable performance in search, they should also produce comparable performance in enumeration. That is, if there are no differences between real-and illusory contours in search, there should also be none in enumeration.

In the sections that follow, we will first investigate differences between line-ending illusory contours in search, in partial replication of Li et al. (2008), investigating the ability find a single vertical target in 4, 6, 8, or 12 horizontal distractors when the items are defined by line-ending illusory contours and the corresponding real-contour controls. We will then will follow up by investigating the effects of the figure type in simple enumeration (enumerating 1–8 vertical targets) and selective enumeration (enumerating 1–8 vertical targets in 4 or 8 horizontal distractors). Carrying out this sequence of studies will enable us to accomplish two goals at once, one related to search and another to enumeration, though achieving them will entail different statistical analyses, as discussed in the sections below.

1. Analyses relevant to the study of search

Our first goal was to provide a conceptual replication of the search study by Li et al. (2008). This will enable us to learn a little more about line-ending illusory contours, but more important it will tell us about the usefulness of the visual search as a predictor of performance in related tasks that require finding targets among distractors. In order to make direct comparisons between search and enumeration tasks, it is important to use conditions where the displays are identical, as occurs when there is only a single target to enumerate in selective enumeration (a direct analogue to target present trials in search). In this way, we know that any differences are due to the task rather than the display. Li et al. (2008) found no significant differences between line-ending illusory contour figures and the corresponding real-contour controls in distractor costs (RT slopes in target present trials) and consequently, there is no reason to expect differences in distractor costs between illusory contours and the real-contour controls in selective enumeration (the increase in RT to enumerate a single target as a function of the number of distractors). If there are no differences between real and illusory contours in both tasks, the results of the search task replicate and this suggest that the search task is useful in predicting performance in other tasks that require finding targets among distractors.

However, it is also possible that differences in distractor costs between real and illusory contours may emerge in selective enumeration that were not evident in search. That pattern of results may indicate that the search task is subject to floor effects that disguise differences between conditions when search is efficient (distractor costs < 10 ms/distractor). If that is true, if there was a way to make the search task more difficult, differences between real and illusory contours would emerge.

Nonetheless, it is also possible that this result could reflect differences in the way that participants approach search and selective enumeration, particularly as it relates to the issue of target localization. The standard search task only requires a target present/target absent decision, and that does not necessarily require that the participants know the actual location of the target at the end of the trial – though they might. However, in standard search tasks where there is only a single type of target and distractor they might also achieve accurate performance by simply responding based on a global sense of homogeneity/heterogeneity (e.g., Duncan & Humphreys, 1989; Thornton & Gilden, 2007) – a sense that items are uniform (target absence) as compared to a sense that there is something different from other things in the display (target presence). Localization is sufficient but not necessary for accurate response in standard search. Therefore, it is possible that participants might achieve efficient search (low distractor costs) in different ways for the real and illusory contours, with localization only occurring for the real-contour controls.

In contrast, for enumeration, target location is critical. In static displays with identical targets, the only thing that distinguishes one target from another is location. Accurate enumeration requires that each target be enumerated once and only once, and this requires distinguishing targets from one another so they are not missed or enumerated twice (item individuation, see Pylyshyn, 1989). Thus, differences in distractor costs between real and illusory contours might emerge in selective enumeration because enumeration requires target localization; participants could no longer rely on a global sense of heterogeneity/homogeneity in order to make an accurate response. If participants achieved efficient search (low distractor costs) in different ways for the line ending illusory contours and the real-contour controls, this difference might manifest itself in selective enumeration.

2. Analyses relevant to the study of enumeration

Our second goal relates to the study of subitizing and counting, operations used in the *accurate* enumeration of small and large numbers of visual items (Kaufman et al., 1949). These analyses will require consideration of the full range of target numerosities (1–8). That is because the most critical measures are the discrepancies in target RT slope (the increase in RT with each additional target) between 1–3 and 6–8 items indicative of the transition between subitizing and counting with the increase in the number of targets. These discrepancies in RT slope only emerge with some types of display though; there are cases where participants use the same slow operation (counting) for both small and large numbers of items (Trick & Pylyshyn, 1993, 1994).

The results of these investigations are important to the study of enumeration because they challenge several theories of enumeration. Most enumeration studies involve uniform black dots presented in isolation against a blank background. Consequently, most theories of enumeration can only explain performance with this type of display (e.g. Contour density theory: Atkinson, Campbell, & Francis, 1976; Pattern theory: Mandler & Shebo, 1982). These theories have no role for attentional selection, and thus, they cannot explain selective enumeration (enumerating targets in distractors). Moreover, because these theories were designed to explain solid uniform black dots presented in isolation, they have difficulty explaining subitizing and counting for figures defined by line-ending illusory contours or the corresponding real-contour controls, especially given that these items are presented against a background of lines.

In contrast, based on the attention-based theory of enumeration (Trick & Pylyshyn, 1993, 1994) subitizing and counting should be evident in simple enumeration for both line-ending illusory contours and the corresponding real-contour controls, though this theory also predicts that the attentional demands (distractor costs) will dictate whether subitizing or counting will be evident in selective enumeration. That is, in conditions where distractor costs are low, there is reason to expect the discontinuities in target RT slope indicative of subitizing and counting in selective enumeration. In contrast, when distractor costs are high in selective enumeration, there should only be evidence of counting, that is, the target RT slopes should be generally high, and there should be no discontinuities between enumeration slopes in the 1–3 and 6–8 item range.

3. Experiment 1: visual search

With Li et al. (2008: Experiment 7) as a model, we created line-ending illusory contours and the corresponding real-contour controls, using the two most extreme conditions. In that study, participants were searching in displays where the items were presented against a background grid of diagonal lines, looking for targets (bars) presented in 4, 6, 8 and 12 distractors when targets and distractors differed in line orientation. They compared performance when the bars were defined by line-ending illusory contours with the corresponding real-contour controls. Results indicated no significant differences in distractor costs between illusory contours and the real-contour controls. In both cases, search was deemed efficient because the RT slopes were < 15 ms/distractor. Our study was not an exact duplicate of their study (the displays were slightly different and there were fewer conditions, for example), but we expected our findings to replicate the original study, with no significant differences between line-ending illusory contours and the corresponding real-contour controls.

3.1. Methods

3.1.1. Participants

We tested 19 undergraduate students with normal or corrected to normal vision recruited from the University of Guelph psychology participant pool, with participants ranging in age between 18 and 22 (14 females). In this and all the following studies, we used the following strategy for determining sample size. We used a repeated measures design and were primarily interested in the differences between real- and illusory contours in RT-related measures. G*Power 3 analysis suggested that a sample size of 15 would be sufficient to reveal differences with an adequate power (0.80) given effect sizes of 0.25 and the correlations we observed among repeated measures. Thus, the number of participants was deemed adequate, especially given that Li et al. (2008) was based on a sample size of 18.

3.1.2. Materials and stimuli

A Macintosh desktop computer was used for testing; participants were seated 70 cm from the display. In this study, participants were required to indicate the presence of targets (vertical bars) against a background grid of lines when items were defined by real as compared to illusory contours. In designing the displays, we tried to replicate conditions in the seventh experiment in Li, Cave, and Wolfe (2008, pp. 485–486) as closely as we could. All stimuli were presented against a background grid of black diagonal lines (2.46 cd/m^2, RGB: 0,0,0) displayed against white (78.79 cd/m^2, RGB: 255,255,255), which means the contrast was high between white and black areas (94%). These 0.03° thick black lines were 0.14° apart, angled at 45°.

The positions of the stimuli were chosen randomly from a 7 × 7 invisible grid that occupied an 8.53° × 8.53° area, though a random jitter of up to 0.12° was introduced to prevent items from being perfectly aligned (minimum inter-item distance = 0.41°). The targets were 0.41° × 0.82° vertical bars, whereas the distractors were the same figures rotated by 90°. For real-contour figures, object boundaries were defined by 0.05° thick black lines (2.46 cd/m^2). These lines were absent in illusory contour figures, which means that there were no actual object boundaries, though there were a series of disconnected edge points produced by the sudden termination of the diagonal background texture in that area. We constructed search displays where participants were looking for vertical targets in 4, 6, 8 or 12 distractors (display sizes 5–13) as in Li et al. (2008).

3.1.3. Procedure

Participants were seated in front of a computer screen. Their task was to hit a "z" key if a vertical target was present and a "," key when the target was absent as accurately and quickly as possible. Accuracy was stressed over speed. Each trial was preceded by a 0.5 s central fixation cross. It is important to note that in this study and both of the enumeration studies that follow, there were no eye movement controls other than the use of a central fixation at the start of the trial. Although eye movements may have an effect on performance our primary goal was to replicate Li et al. (2008), a study that did not employ eye movement controls. Furthermore, the most common way to control eye movements is to limit exposure duration. This practice may force the participants to use a different process than they might normally use to carry out the task (e.g., see MacInnes, Hunt, Hilchey, & Klein, 2014). Subitizing and counting are not caused by eye movements; there is evidence of the differences in processes regardless of whether trials with eye movements are analyzed or excluded (see Trick & Pylyshyn, 1994 for a review). However, preventing eye movements by limiting exposure durations makes it impossible to make meaningful comparisons of RT at different ranges of numerosity because the error rates are so high with larger numbers of items as compared to lower numbers (Jensen et al., 1950). For example, Mandler and Shebo (1982) showed error rates between 70 and 80% with 7 and 8 items though the corresponding error rates were close to zero with 1–3 (Fig. 3). Only RT from correct trials are submitted for analysis; almost all the trials are analyzed when there are 1–3 items but a decreasing percentage of trials are used in RT analysis with larger numbers. When participants are wrong more often than they are right, there is reason to wonder if the rare correct trial represents a lucky guess.

In the present study, participants did two blocks with 120 trials each, one with targets and distractors defined by actual contours (the real-contour controls) and the other with items defined by line-ending illusory contours. The order of block presentation was counterbalanced across participants. Display size and target presence varied randomly within each block. Before each block, participants did 15 trials of practice with each type of figure.

3.2. Results and discussion

For this and all following experiments, data were analyzed using repeated-measures ANOVA with the Greenhouse-Geisser correction applied as needed for violations of the sphericity assumption. Effect size was measured by partial eta-squared (partial η^2). We measured search performance as a function of figure (illusory contours, real-contour controls), target presence (target present and target absent trials) and display size (5, 7, 9, 13). For each participant, RT in excess of 2.5 SD away from that individual's specific mean for that cell were dropped from the analysis.

As can be seen from Table 1, the results of our slope analysis replicate those from Li et al. (2008, page 486), showing no differences in RT slope between the illusory contours and the corresponding real-contour controls. Figure type had no significant effect on RT slopes in search (F(1,18) = 0.03, p = .86). Although RT slopes were steeper for target absent than target present trials (F(1,18) = 16.59, p = .001, partial η^2 = 0.48), there was no Figure X Target Presence interaction (F (1,18) = 0.52, p = .48). In fact, there were no significant differences between the line-end illusory contours and real-contour controls in terms of either distractor costs (target present slopes) or target absent slopes (F < 1 for both).

Table 1
Experiment 1: Target present and target absent slopes in milliseconds per distractor for real-contour controls and line-ending illusory contours as compared to those of Li, et al. (2008, Experiment 7). Note: Target present slopes are referred to as distractor costs in the document. Standard errors listed in parentheses.

	Our stimuli: n = 19		Li et al. (2008): n = 18	
	Real contour figure	Illusory contour figure	Real contour figure	Illusory contour figure
Target present	1.38 (3.08)	−0.72 (1.73)	13.2	13.0
Target absent	14.70 (2.35)	15.78 (2.84)	38.8	46.1

Li et al. (2008) did not include analyses of error and RT though RT were graphed. For the sake of completeness, we analyzed the error and RT data in our study (Figs. 2 and 3 respectively). Error rates were very low overall (M error rate = 2.1%). Nonetheless, there was a significant difference between the illusory contour figures and the corresponding real-contour controls, though interestingly, the error rate was significantly higher for the real-contour controls than the illusory contour figures (M difference in error = 1.5%; F (1,18) = 6.72, p = .02, partial η^2 = 0.27). The only other effect that was statistically significance was the Display Size X Target presence interaction (F (2.66, 47.95) = 3.15, p = .032, partial η^2 = 0.15), with error rates especially high for display size 5 in the target absent trials and display size 9 for target present trials. Otherwise there were no significant effects (Target presence: F (1,18) = 0.15, p = .70; Display size: F (2.34, 42.11) = 1.72, p = .17; Figure X Target presence: F (1,18) = 0.002; p = .97; Figure X Display size: F (2.61, 46.99) = 0.64, p = .60; Figure X Target Presence X Display size: F (2.68, 48.26) = 1.68, p = .18).

On average, RT were significantly lower for the real-contour controls than the corresponding illusory contours (M difference = 53 ms; F (1,18) = 17.69, p = .001, partial η^2 = 0.50). There were also main effects of target presence (F(1,18) = 12.79, p = .002, partial η^2 = 0.42) and display size (F(2.23, 40.08) = 16.05, p < .001. partial η^2 = 0.47). A Display size X Target presence interaction emerged (F(2.20, 39.57) = 10.43, p < .001, partial η^2 = 0.37) such that display size had a stronger effect on target absent than target present trials, consistent with the analyses showing significant differences in RT slope. Otherwise none of the interactions were significant (Figure X Target presence: F (1,18) = 1.25, p = .28; Figure X Display size: F(2.1, 37.75) = 0.16, p = .92; Figure X Target Presence X Display size: F(2.51, 45.10) = 0.45, p = .72).

In summary, our results replicated Li et al.'s (2008) data in showing no significant differences in distractor costs between illusory contours and the corresponding real-contour controls. RT analyses were not included in Li et al. (2008), but we found a main effect of figure type on RT, with search for illusory contours 53 ms slower than the corresponding real-contour controls. This RT difference apparent even in target present trials with only 4 distractors (M difference = 44 ms, F (1,18) = 6.26, p = .022, partial η^2 = 0.26) though error rates for real and illusory contour figures with this number of distractors were almost identical (M difference = 0.5%; (F(1,18) = 0.11, p = .75).

The results show an overall difference in RT between the line-ending illusory contours and the real-contour controls that is not mirrored in RT slopes. This difference in conditions must reflect the influence of global factors that affect the entire display. It is possible this might indicate differences in visibility of the items against the background, reflecting differences in the contrast between the items and the background. However, contrast generally refers to an overall difference in brightness between a solid item and uniform background. It is more complex in this context, given that the background was made up of alternating light and dark diagonal lines and the illusory contours were defined by dark points of light with light areas between them.

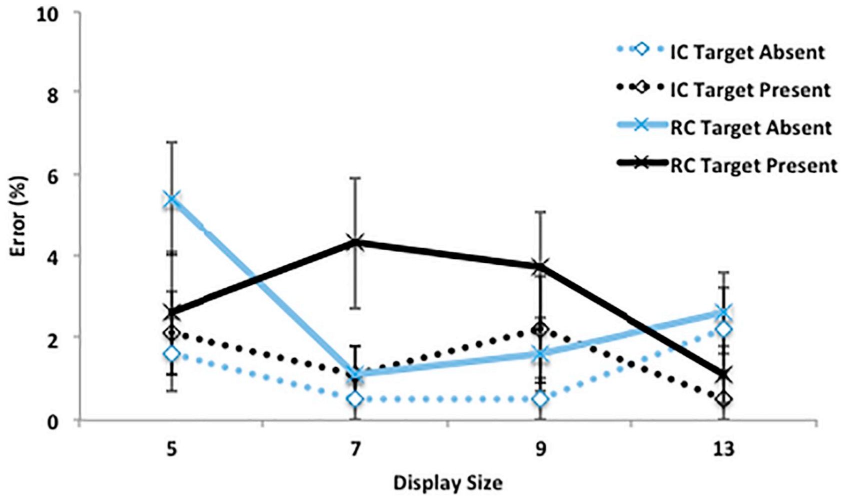


Fig. 2. Mean percent error for search task where participants were searching for vertical bars in horizontal distractors (Experiment 1), comparing performance for target present and target absent trials when items were defined by line-ending illusory contour figures (IC) and real-contour controls (RC). Standard error bars included.

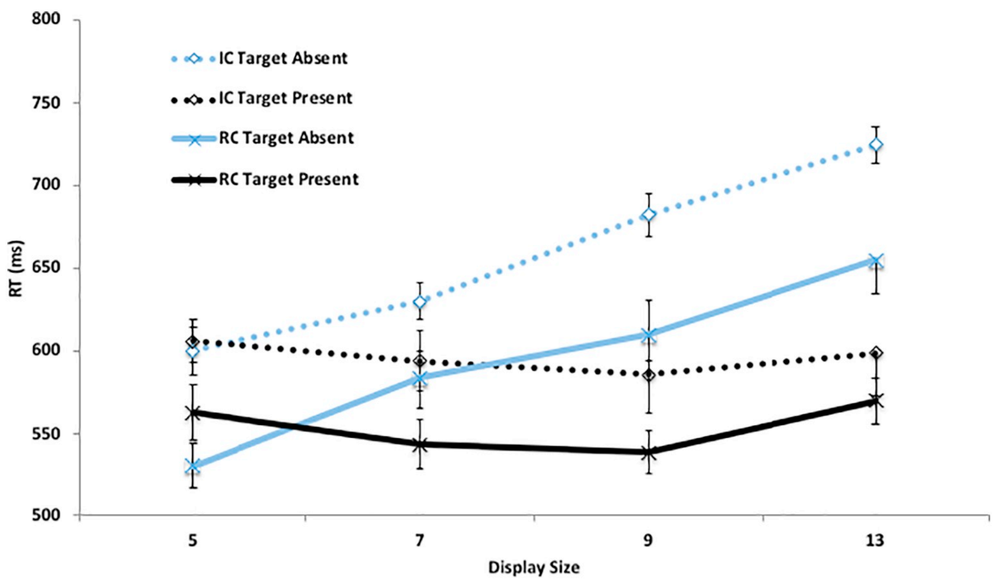


Fig. 3. Mean RT in milliseconds for search task where participants were searching for vertical bars in horizontal distractors (Experiment 1), comparing performance for target present and target absent trials when items were defined by line-ending illusory contour figures (IC) and real-contour controls (RC). Standard error bars included.

Alternatively, given that the illusory contours figures were made up of disconnected edge points, it may be productive to consider a distinction first made by Koffka (1935), Koffka noted that defining a shape from disconnected edge points contours requires two operations: 1) gathering together the relevant disconnected edge points to define a unit (the cluster of contours used to define a proto-object) and 2) using those selected edge points to define a shape (e.g. a vertical or horizontal bar). Because search tasks require distinguishing targets from distractors, search tasks involving illusory contours require both of those operations. Consequently, from this perspective there are two possible explanations for the difference in overall RT between real and illusory contours in search. The first is that differences in RT between the real and illusory contours are solely due to the disconnected edge points in the illusory contour figures, requiring Koffka's grouping operations (stage 1) to draw together relevant edge points to define units. The second is that the differences in RT were due (or also due) to the need define shapes (horizontal and vertical bars), making use of those disconnected contours (Koffka's second stage). Regardless these operations would have to take place all across the image at once to explain how there could be differences in overall RT between conditions though no differences in distractor costs.

However, distinguishing between Koffka's first and second stages requires some sort of distractor-free task where the grouping demands of the illusory contours could be examined without the need for the shape definition (necessary for distinguishing between the vertical and horizontal bars). Enumeration is such a task. Consequently, in Experiment 2, we tested participants in a simple numeration task where participants were enumerating 1–8 targets when the targets were presented in isolation. From the perspective of search, the index of primary importance is the enumeration performance for a single target, where there is no need to distinguish targets from distractors or for that matter, targets from other targets in the display.

4. Experiment 2: simple enumeration

In Experiment 2 we compared line-ending illusory contours and the corresponding real-contour controls in a simple enumeration task (targets but no distractors). When comparing the search and enumeration, if the main effect in RT seen search were due to the grouping demands imposed by the need to see items defined by disconnected edge points, then there should be significant differences in RT and error rates between real and illusory contours even when there is only single target in enumeration. In contrast, if the differences between real and illusory contours emerge because the shape definition process necessary when distinguishing target shapes from distractors was more difficult for illusory contour figures, then there should be no significant difference between the real and illusory contour figures.

The results are also of interest as it relates to the enumeration literature. It has long been known that at least in some conditions, there are marked differences in processing between small and large number of target items (e.g., Jensen et al., 1950; Maylor, Watson, & Hartley, 2011; Trick & Pylyshyn, 1993, 1994; Watson et al., 2002). These effects can be seen in terms of the shape of the enumeration function: the function that plots the overall time to enumerate a given number of items as it varies with the total number in the display. When that occurs, there may be changes in the relative size of RT slopes for small and large numbers of items (RT slope = the increase in enumeration response time with each additional target to enumerate).

Typically, when there are fewer than 4 or 5 items, the increase in RT with each additional item is small, whereas when there are > 5, the increase is much larger. *Subitizing* is the name of the fast, accurate, effortless, processes when there are small numbers whereas *counting* is the name given to the slower and more effortful process used when there are more (Jensen et al., 1950; Kaufman et al., 1949; Mandler & Shebo, 1982). There are case-by-case differences based on display conditions (image contrast, the presence of background contours), but typically in studies where young adults enumerate high-contrast dots presented against a blank background, the RT slopes for 1–3 or 1–4 items vary between 40 and 120 ms/target (see Trick & Pylyshyn, 1994, Footnote 1, for a discussion of factors that cause absolute slopes to vary). Counting slopes are significantly higher. For example, dot enumeration studies typically report RT slopes of 200–350 ms/target when there are > 5 dots in the display, though display conditions can also affect absolute RT slopes in the counting range as well (e.g., Van Oeffellen & Vos, 1982).

Interestingly, in studies of accurate enumeration, although there is always evidence of counting, subitizing only emerges with some types of enumeration task. When the attentional demands of an enumeration task are low, there is evidence of subitizing (Trick & Pylyshyn, 1993, 1994). When that happens, there are significant differences in the RT slopes between small and larger numbers of items. In contrast, when attentional demands of the task are higher, there is no evidence of subitizing (Trick & Pylyshyn, 1993, 1994). That is, there is no significant difference in the RT slopes between small and larger numbers of items, and moreover, the RT slopes are high throughout the number range (e.g., 1–8), producing an enumeration function that looks roughly linear.

In these analyses, error and RT through the 1–8 range are analyzed, but we also used regression to calculate the RT slopes for 1–3 and 6–8 targets. We chose those specific ranges because most young adults can subitize at least up to 3 and most count when there are 6 or more, though there are individual differences in the maximum number that can be subitized (Trick, 2008; Watson & Maylor, 2006). If grouping the disconnected elements in the illusory contour figures to form the integrated units to be enumerated made few attentional demands, the RT slope differences between 1–3 and 6–8 items would be evident for both types of figure; subitizing and counting would be evident for both. Furthermore, there would be little difference between the illusory contours and real-contour controls in terms of RT slopes, particularly in the 1–3 range. In contrast, if grouping the disconnected endpoints in the illusory contour figures to form the integrated units to be enumerated made attentional demands, then there would be an interaction between figure type and range when it came to RT slopes. Specifically, for the real-contour controls, there would be significant differences in RT slopes between the 1–3 and 6–8 item ranges, whereas for illusory contours there would not, as would be expected if the attentional demands of integrating disconnected elements to form a unit were too high to permit subitizing. If that occurred participants would be obliged to use the relatively slow counting process for both small and large numbers of items for illusory contour figures and thus there would be no difference in RT slopes between different ranges.

4.1. Method

4.1.1. Participants

Nineteen participants were recruited from the University of Guelph participant pool and paid in course credit (females = 13). All were between 18 and 20 years of age and had normal or corrected to normal vision. This sample size was deemed adequate to distinguish the effects of figure type given the correlations in RT typical in enumeration study. Given that the primary interest was in analyses comparing real from illusory contours, in this within subjects design, a sample size of 15 would be sufficient to reveal differences with an adequate power (0.80) given effect sizes of 0.25 and the correlations we observed among repeated measures in enumeration studies.

4.1.2. Materials

The stimuli and materials were the same as in Experiment 1 except the displays had 1–9 targets (vertical bars) and no distractors. Although up to 9 were presented, only data from trials with 1–8 targets were analyzed due to end effects in RT (Mandler & Shebo, 1982). End effects occur when participants learn the maximal number of items in the display (n), and thus begin guessing "n" whenever there are large numbers of items producing an artificial drop in RT.

4.1.3. Procedure

In the instructions for the enumeration task, accuracy was given more emphasis than speed. Participants were instructed to *accurately* enumerate the targets in the display, going as quickly as they could while maintaining accuracy. Participants were allowed to enumerate normally though (there were no eye movement constraints after the initial fixation point). In each trial, participants were first shown a 0.5 s central fixation cross before the enumeration display appeared. Once the enumeration display appeared, it remained until participants pushed the space bar to indicate that they knew the number of targets in the display (the timed portion of the trial). The display disappeared, and they then typed in the number of targets (error feedback was given). This two-stage procedure avoids confounding perceptual enumeration time with the time required to find a given digit on the keyboard, and it has been used in other studies (e.g., Trick, 2008; Watson & Maylor, 2006). Participants did a total of 198 trials of enumeration. Figure type (real, illusory contour) was blocked and the order counterbalanced. The number of targets was randomized. Participants did 15 practice trials before they did the corresponding block of experimental trials.

4.2. Results and discussion

Percentage error and enumeration RT for correct trials were analyzed though RT were first screened for outliers. For each participant, condition, and number of targets, trials in which the RT was > 2.5 SD away from the participant's respective mean for that condition and number of targets were dropped. This resulted in the loss of 1.60% of the trials.

4.2.1. Analyses relevant to the study of search

Analyses were conducted assessing the effect of figure type (illusory contour, real-contour control) on enumeration performance for a single item. The average error rate was extremely low when participants enumerated a single item (M = 1.2%) and there were no significant differences between the line-ending illusory contours and the corresponding real-contour controls (F (1,18) = 0.20, p = .66). However, there were significant differences between the two conditions in terms of enumeration RT: F (1, 18) = 5.45, p = .031, partial η^2 = 0.23. Enumeration was 70 ms slower for the line-ending illusory contours with 19 participants. (The difference was also statistically significant after the data from 3 participants with high error rates in the 6–8 item range were dropped: F (1,15) = 5.14, p = .039, partial η^2 = 0.26, M

difference = 80 ms.) Thus, the overall difference in RT observed in search was replicated in enumeration, even when there was only a single target presented in isolation. These results suggest that items made up of disconnected edge points may be less visible perhaps because operations involved in drawing together the relevant edge points take time. The difference emerges even when there is no need to distinguish target shapes from distractors – or that matter, targets from other targets in the display.

4.2.2. Analyses relevant to the study of enumeration

Analyses were conducted assessing the effects of figure type (illusory contours, real-contour controls) and number (1–8) on enumeration performance (error rates, RT). The instructions for the enumeration task emphasized accuracy. However, as is often the case in enumeration studies, there are some participants who do not follow the directions, an effect that is especially notable when enumeration is at its most time consuming, at the top of the number range. When faced with a large number of items, some people estimate rather than count. Counting is slow and fairly accurate; estimation is extremely fast but inaccurate. When people estimate, answers are often wrong, but "in the ball park". *Estimation* has been shown to involve different processes and brain areas than subitizing and counting (e.g. Burr et al., 2010; Piazza, Fumarola, Chinello, & Melcher, 2011; Revkin, Piazza, Izard, Cohen, & Dehaene, 2008).

In the studies described in this paper, when looking at the full range of numerosities, we were interested in comparing subitizing and counting – both reasonably accurate processes. Guessing and estimation are not. It makes little sense to combine data across participants who are using different strategies to accomplish the same task because the resulting average will not be an accurate reflection of either process (Siegler, 1987). Consequently, to avoid mixing data from participants who were counting with that of those who were estimating or guessing, we used a protocol that has been employed in other enumeration studies (e.g. Trick, 2008; Watson & Blagrove, 2012). Specifically, we dropped the data for participants with error rates of 30% or more in one or more conditions. Based on these criteria, the data from 3 participants were dropped in the analyses that involved the full range of numerosities (1–8). These individuals had error rates as high as 55% in one or more conditions in the 6–8 item range.

4.2.2.1. Error. Error rates in the 1–8 range are shown in Fig. 4. On average, the error rate was low (M = 2.0%) as might be expected if participants were subitizing and counting rather than estimating or guessing. As is typical in enumeration studies, number had a significant effect on error (F (4.1, 61.52) = 2.39, p = .026, partial η^2 = 0.14), but there were no other significant effects (Figure: F (1, 15) = 1.63, p = .23; Figure X Number: F (4.22, 63.31) = 1.0, p = .43 respectively).

4.2.2.2. RT. There was the usual increase in RT with the number of targets (F (1.70, 25.55) = 170.98, p < .001, partial η^2 = 0.92) as shown in Fig. 5. On average, across the 1–8 range, participants were 65 ms slower to enumerate illusory contour figures than the corresponding real contour controls (SE = 41.6). However, differences in RT between the real-and illusory condition ranged from 100 ms and 125 ms at 5 at 6 targets to 6 and 12 ms at 7 and 8 targets. Thus, although the difference between conditions was statistically significant when there was only a single item to enumerate (M difference = 80 ms for those involved in the enumeration analysis, p < .05), the main effect of figure type did not achieve statistical significance across the range (F(1,15) = 2.41, p = .14, η^2 = 0.14). The Figure X Number interaction did not achieve statistical significance either though (F (2.86, 42.82) = 0.65, p = .72).

4.2.2.3. Target RT slopes. Slopes for the 1–3 and 6–8 target range were calculated using regression, and the effects of figure type (illusory contours, real contour controls) were assessed as a function of range (1–3 target range, 6–8 target range). RT slopes were significantly lower in the 1–3 than the 6–8 item range (see Table 2), as would be expected if participants could use the fast, accurate, subitizing operation to enumerate small numbers of targets (F (1, 15) = 29.50, p < .001, partial η^2 = 0.66). None of the other effects achieved significance (Figure: F (1,15) = 1.94, p = .19; Figure X Range: F (1,15) = 0.88, p = .36)

Overall, the results of this experiment showed that the need to cluster disconnected contours slowed enumeration slightly, but it did not prevent subitizing and counting. The RT slope discontinuities between small and large numbers of items emerged as usual, and in fact, there were no RT slope differences between the line-ending illusory contours and the corresponding real-contour controls in either the subitizing or the counting range (F (1,15) = 0.59, p = .46; F (1,15) = 1.43, p = .25 for the 1–3 and 6–8 ranges respectively). Although the illusory contour condition involved individual items (units) defined by disconnected contours, this did not seem to make the sort of attentional demands that make it impossible to subitize.

These results are consistent with those of Trick and Enns (1997a), where participants were asked to enumerate figures on a blank screen when figures made up of connected lines as compared to disconnected dots. Subitizing and counting emerged in both conditions and there

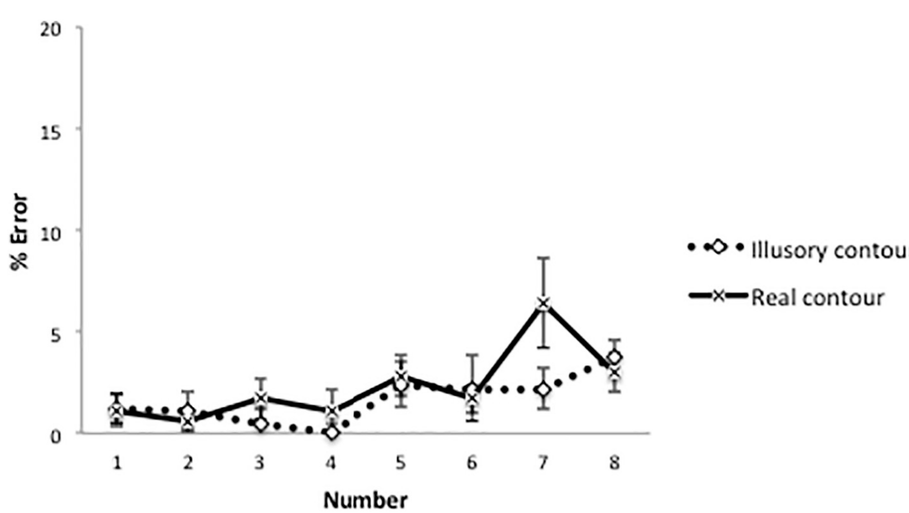


Fig. 4. Mean percent error for enumerating 1–8 vertical targets for line-ending illusory contour figures and the real-contour controls in the simple enumeration task (Experiment 2). Standard error bars included.

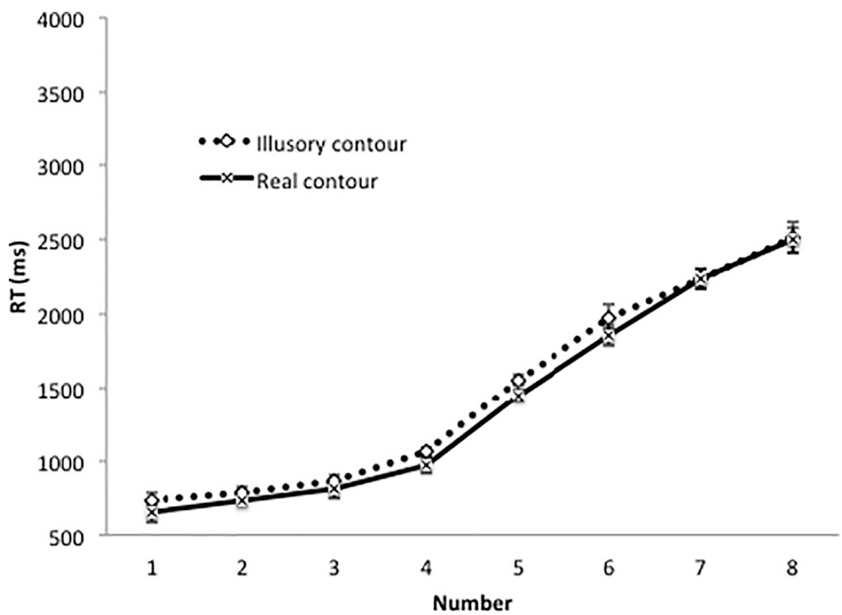


Fig. 5. Mean enumeration response time (RT) in milliseconds for enumerating 1–8 vertical targets for line-ending illusory contour figures and the real-contour controls in the simple enumeration task (Experiment 2). Standard error bars included.

Table 2
Experiment 2: Enumeration RT slopes in milliseconds/target for the 1–3 and 6–8 item ranges in the simple enumeration task for the real-contour controls and line-ending illusory contours. Standard errors listed in parentheses. Note: RT slopes in enumeration studies mean the increase in RT with each additional target to enumerate.

	Real contour figure	Illusory contour figure
1–3 target range	75.42 (23.73)	65.83 (19.03)
6–8 target range	323.24 (32.44)	265.00 (31.37)

were no significant differences in RT slopes, as in this study. However, in that study care was taken to ensure that both types of item had exactly the same number of darkened pixels so that the brightness contrast between the items and the background was exactly the same for the connected and disconnected items. This may explain why there was no sign of the 70–80 ms discrepancy in RT between the connected and disconnected figures for one item in Trick and Enns though there was in the present study. Brightness contrast (items against the background) has been shown to affect enumeration performance (Simon, Peterson, Patel, & Sathian, 1998), and it is possible that that factor was at work in this study. It is important to reiterate that this difference between connected and disconnected items was not significant across the entire number range though; the RT difference between the illusory contours and line-ending controls disappeared when there were 7 or more items, perhaps obscured by the greater variability associated with range of operations involved in counting larger numbers of items, including eye movements (e.g. Watson et al., 2007).

Overall, the pattern of results is consistent with predictions of the attention-based theory of enumeration (Trick & Pylyshyn, 1994), which incorporates subitizing and counting into a theory of vision. According to this theory, subitizing relies on the operation of an item individuation mechanism that can individuate small numbers of items at once. This mechanism operates after low level vision (defining contours and grouping them into clusters or proto-objects), but before the one-area-at-a-time operations associated with moving the focus of spatial attention across the display.

5. Experiment 3: selective enumeration

The first two experiments showed that although RT were overall higher for illusory contours than the real-contour controls, there were never differences in RT slopes either in terms of distractor costs (target present slopes in search) or target RT slopes in enumeration. Experiment 2 showed that the differences between real and illusory contour figures emerged when a single target was presented in isolation, which suggests that it may be harder to see an item (or people may be slower to see items) defined by disconnected edge points, even in situations where there is no need to distinguish between items based on their shapes (targets and distractors). This effect manifest itself in terms of a global delay (main effects in RT) rather than by an item-by-item delay (RT slopes).

In Experiment 3 we combined the search and enumeration tasks to create a selective enumeration task where participants were required to enumerate 1–8 vertical targets among 4 and 8 horizontal distractors (distractor numerosities used in Experiment 1). The selective enumeration task provides two useful indices of performance. First, there are distractor costs, that is, the increase in RT to enumerate a *single* target as a function of the number of distractors, a direct analogue to the corresponding measure of distractor costs in search: target present slopes. Second, there are target RT slopes, the increase in time required to enumerate a single target as a function of the number of targets, and in particular, the RT slope discontinuities between small and large numbers of targets (1–3 and 6–8) indicative of subitize and counting.

As it relates to search, if distractor costs in search are a good index of the attentional demands of finding a single target in distractors in enumeration, there should be no significant difference in distractor costs between the illusory contours and the corresponding real-contour controls in selective enumeration when enumerating a single target with 4 or 8 distractors. (These displays are identical to those in target present trials with 4 and 8 distractors.) Although distractor costs in selective enumeration might be slightly higher than the corresponding costs in search (people may feel the need to do extra checking to ensure there are no other distractors), the pattern of the results should be the same. There should be no significant differences between line-ending illusory contour and the corresponding real-contour controls.

Furthermore, given that both real and illusory contours required enumerating vertical targets in horizontal distractors, there is reason to expect subitizing and counting for both, based on other selective enumeration studies that involved enumerating vertical targets in horizontal distractors (Trick and Enns, 1997a, b, Trick & Pylyshyn, 1993, 1994). That is, there is reason to expect the discontinuities in target RT slopes between 1–3 and 6–8 targets to emerge for both the line-ending illusory contours and the real-contour controls.

Conversely, if the illusory contour figures make attentional demands beyond those required for the real-contour controls, there is reason there could be differences between illusory contours and the corresponding real-contour controls that emerge in selective enumeration though none were evident in the corresponding search task. In particular, this should manifest itself in terms of significant differences between real and illusory contours in distractor costs when enumerating a single item (increase in RT as a function of the number of distractors). Moreover, the target RT slope discontinuities between 1–3 and 6–8 items indicative of the change from subitizing to counting should occur with the real-contour controls but not the corresponding illusory contour figures.

5.1. Method

5.1.1. Participants

The participants were 25 undergraduate students recruited from the participant pool and paid in course credit (none were involved in the preceding studies). Participants were between 18 and 22 and had normal or corrected to normal vision. This sample size was deemed more than adequate given that a sample size of 15 would be sufficient to reveal differences between two conditions in a within subjects design (sufficient to achieve a power of 0.80 to find effect sizes of 0.25 given the correlations between repeated measures).

5.1.2. Materials and procedure

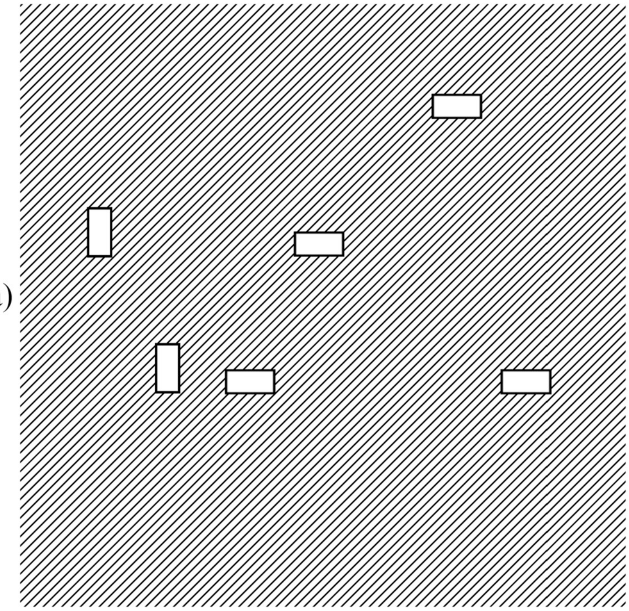
The targets and distractors were as describe in Experiment 1. Displays featured 1–9 targets (vertical bars) and either 4 or 8 distractors (horizontal bars) when the items were defined by line-ending illusory contours or the corresponding real-contour controls (see Fig. 6). We used 4 and 8 distractors because those were two of the conditions in Experiment 1 (cf. Li et al., 2008). Moreover, this guaranteed that at least in most trials, the total number in the display (targets + distractors) was less than the maximal display size in Experiment 1 (search). Given the maximum display size in search was 13, participants could enumerate 1–8 items in 4 distractors and still have a lower total number of items than in search. Similarly, participants could enumerate 1–4 targets among 8 distractors and still have fewer items than the maximal display size in search. Thus, although total item density in selective enumeration could be greater than that for search, in many cases it was not.

Participants were instructed to accurately determine the number of vertical bars in the display, going as quickly as they could while at the same time ensuring accuracy. Accuracy was emphasized over speed. As in Experiment 2, each trial began with an initial fixation cross (0.5 s) and then the display appeared and remained until the participant pushed the space bar (the timed portion) and then they typed in the number of items at their leisure. Moreover, as in first two experiments, figure type (illusory contour, real-contour control) was blocked, and the order of presentation was counterbalanced. Participants did 396 trials of enumeration, with the numbers of targets and distractors were both randomized within blocks. Before each block of trials, participants completed 15 trials of practice with the associated figure type.

5.2. Results and discussion

As in Experiment 2, only RTs for correct trials were analyzed and for each participant, RT in excess of 2.5 standard deviations from the mean for that specific number of targets, number of distractors, and figure type were dropped. In this case no trials were dropped.

(a)



(b)

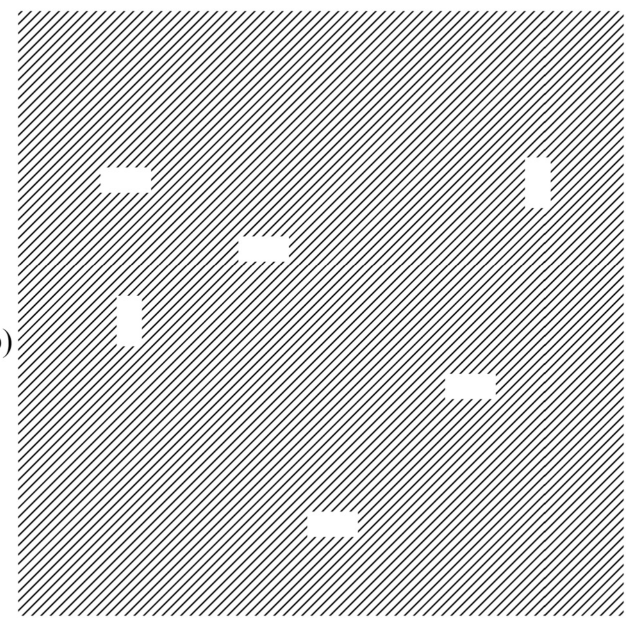


Fig. 6. A portrayal of what a selective enumeration trial with two targets (vertical rectangles) and four distractors (horizontal rectangles) would look like from Experiment 3. (a) Real-contour controls (b) Line-ending illusory contour figures.

5.2.1. Analyses relevant to the study of search

Analyses were conducted investigating the effects of figure type (illusory contour, real contour control) as a function of the number of distractors (4,8) as it affected the time to enumerate a single item. Error rates when enumerating a single item were every low (M = 1.5%). Figure had no significant effect ($F(1,24) = 0.01$, $p = .96$) and the other effects were at best marginal (Number of distractors: ($F(1,24) = 2.39$, $p = .14$, partial $\eta^2 = 0.09$; Figure X Number of distractors ($F(1,24) = 3.53$, $p = .073$, partial $\eta^2 = 0.13$). Although the error rates for illusory contours and the corresponding real contour controls were the same (1.5%), there were large differences in RT ($F(1,24) = 34.64$, $p < .001$, partial $\eta^2 = 0.59$), with enumeration of a single item 480 ms faster for real-contour controls than the corresponding illusory contour figures. Distractors also had an effect on RT, with RT higher as the number of distractors increased ($F(1,24) = 23.18$, $p < .001$, partial $\eta^2 = 0.49$) and there was also a Figure X Number of distractor interaction ($F(1,24) = 27.49$, $p < .001$, partial $\eta^2 = 0.53$) which will be further explored in the discussion of distractor costs.

Of primary interest are the distractor costs (a director analogue to target present trials in search), we focused first on the analyses involving the enumeration of a single target. Distractor RT costs in enumeration were calculated as the increase in RT to enumerate as the number of distractors increased from 4 to 8, and these costs were analyzed as a function of figure type (illusory contours, real-contour controls) Contrary to what might be expected given the results of Li et al. (2008) and Experiment 1, there were large and statistically significant differences in distractor costs between line-ending illusory contour figures and the corresponding real-contour controls. Figure had a powerful effect on distractor costs in selective enumeration ($F(1,24) = 27.49$, $p < .001$, partial $\eta^2 = 0.53$). For illusory contour figures each additional distractor added 146 ms to the time to enumerate a single item whereas it only added 30 ms for the real-contour controls ($SE = 11.09$ and 11.09), a difference of 116 ms. (These effects replicated in the smaller sample when the participants with error rates in excess of 30% in the 6–8 item range were dropped: $F(1, 15) = 32.29$, $p < .001$, partial $\eta^2 = 0.68$; M difference = 134 ms; distractor costs were 130 ms/distractor and − 4 ms/distractor for the illusory contour figures and real-contour controls respectively.)

Thus, though Experiment 1 and Li et al. (2008) showed no differences distractor costs between real and illusory contour figures in visual search (M difference = 1 ms in Experiment 1), there were large and statistically significant differences in distractor costs between real and illusory contour figures in selective enumeration (M difference = 116 ms). A mixed factorial analysis of variance of distractor costs as a function of figure (illusory-contours, real-contour controls) and task (Experiment 1: search, Experiment 3: selective enumeration) revealed significant effects of figure, task, and the figure X task interaction ($F(1,42) = 19.77$, $p < .001$, $\eta^2 = 0.32$; $F(1,42) = 17.32$, $p < .001$, $\eta^2 = 0.29$; $F(1,42) = 21.24$, $p < .001$, $\eta^2 = 0.34$ respectively). This is especially impressive because each display only contained 5 or 9 items (targets + distractors).

5.2.2. *Analysis relevant to the study of enumeration*

To study subitizing and counting it is important to ensure that accuracy was high throughout the range. Although the instructions stressed accuracy, the temptation to guess or estimate tends to be especially acute when enumeration is time consuming. In this study, some of the participants were taking 6–7 s per trial to enumerate displays with higher numbers of targets and distractors and this may have prompted more estimation and guessing. Data from 9 participants with error rates in excess of 30% in one or more conditions were removed (some had error rates as high as 60–80% in one or more conditions). This left 16 participants for the analyses involving the full range of numbers. For these analyses, error rates and RT were measured as a function of figure type (illusory contours, real-contour control), the number of distractors (4, 8) and the number of targets (1–8).

5.2.2.1. Error rates. Error data are presented in Fig. 7. Although the error rates were not as low as in the first study, the average error rate was still reasonably low as might be expected if the participants were subitizing or counting rather than estimating or guessing ($M = 4.80\%$, $SE = 0.50\%$). Nonetheless, there were significantly more errors for illusory contour figures than the real contours (M difference = 3.2%; $F(1, 15) = 5.05$, $p = .04$, partial $\eta^2 = 0.25$). Error rates increased with the number of targets as usual ($F(4.07, 61.05) = 8.23$, $p < .001$, partial $\eta^2 = 0.35$), but otherwise there were no significant effects ($p > .1$).

5.2.2.2. RT. ANOVA revealed that enumeration RT were significantly higher for illusory contour figures than for the real-contour controls (M difference = 718 ms; $F(1, 15) = 18.45$, $p < .001$, partial $\eta^2 = 0.55$) as shown in Fig. 8. Unsurprisingly, RT increased with both the number of targets ($F(2.06, 30.84) = 235.50$, $p < .001$, partial $\eta^2 = 0.94$) and number of distractors ($F(1, 15) = 73.27$, $p < .001$, partial $\eta^2 = 0.83$). Although the 3-way interaction and the Number of targets X Number of distractors interaction were not statistically significant ($F(4.08, 61.18) = 1.0$, $p = .42$; $F(3.80, 56.99) = 1.94$, $p = .12$ respectively), a number of two-way interactions emerged. Both the Figure X Number of Distractors interaction and Figure X Number of Targets interaction were significant ($F(1, 15) = 26.93$, $p < .001$, partial $\eta^2 = 0.64$; $F(3.71, 55.70) = 3.90$, $p = .009$, partial $\eta^2 = 0.21$ respectively). The interaction between figure and the number of distractors has been discussed in the context of distractor costs (previously) but the Figure X Number of targets interaction will be addressed in the following section as it relates to enumeration RT slopes.

5.2.2.3. RT slopes. In order to determine whether there was evidence of subitizing and counting as shown by RT slope discrepancies, and to further investigate the Figure X Number of targets interaction, RT slopes in the 1–3 range were compared with those in the 6–8 target range as a function of figure type (illusory contour, real-contour controls), and number of distractors (4, 8). RT slopes are shown in Table 3. A 2 × 2 × 2 ANOVA revealed a significant main effect of target range ($F(1, 15) = 6.82$, $p = .02$, partial $\eta^2 = 0.31$) qualified by the significant Range X Figure interaction ($F(1, 15) = 6.63$, $p = .021$, partial $\eta^2 = 0.31$).

To examine the nature of this interaction, planned comparisons were performed, examining differences in RT slopes between the 1–3 and 6–8 items separately for the real contour figures and illusory contour figures. The distractor effects will be discussed in the context of these analyses. For the real-contour figures, RT slope was significantly lower for 1–3 than 6–8 targets ($F(1, 15) = 8.64$, $p = .01$, partial $\eta^2 = 0.37$), indicating subitizing and counting emerged as usual. The number of distractors had no significant effect on the enumeration of the real-contour controls but there was as Range X Number of distractors interaction: $F(1,15) = 0.3$, $p = .60$; $F(1,15) = 5.03$, $p = .04$, partial $\eta^2 = 0.25$ respectively. Compared to when there were 4 distractors, with 8 distractors there was an increase in the 1–3 range slopes (while error rates were low) but a marked decrease in 6–8 range slopes (as error rates increased).

In contrast, for illusory contour figures there was no significant difference in RT slopes between 1–3 and 6–8 targets, ($F(1, 15) = 0.34$, $p = .57$), as might be expected if the counting process was being used for both small and large numbers of items when participants were enumerating illusory contour figures among distractors. The number of distractors had a significant effect on slopes for illusory contours ($F(1.15) = 5.57$, $p = .032$, partial $\eta^2 = 0.27$), with RT slopes *decreasing* with the number of distractors as average error rates approached 16%. Distractors posed a significantly greater challenge with illusory contour figures and there began to be evidence of speed-accuracy trade-offs with larger numbers of distractors (reductions in RT slopes accompanied by marked increases in error).

In fact, overall figure had an interactive effect on RT slopes in enumeration (Range X Figure interaction ($F(1, 15) = 6.63$, $p = .021$, partial $\eta^2 = 0.31$). Compared to the real-contour controls, target RT slopes were higher for the illusory contours in the subitizing range (M difference = 118 ms) and lower in the counting range (M difference = 107 ms). This result may be partly explained by speed accuracy trade-offs in the 6–8 item range, particularly for the illusory contour condition. As the number of targets increased from 6 to 8 in the illusory contour condition, average error rates approached 16%. For illusory contours, as error rate climbed in the 6–8 item range, RT slopes dropped. Overall this study revealed large and statistically significant differences between the line-ending illusory contours and the corresponding real-contour controls.

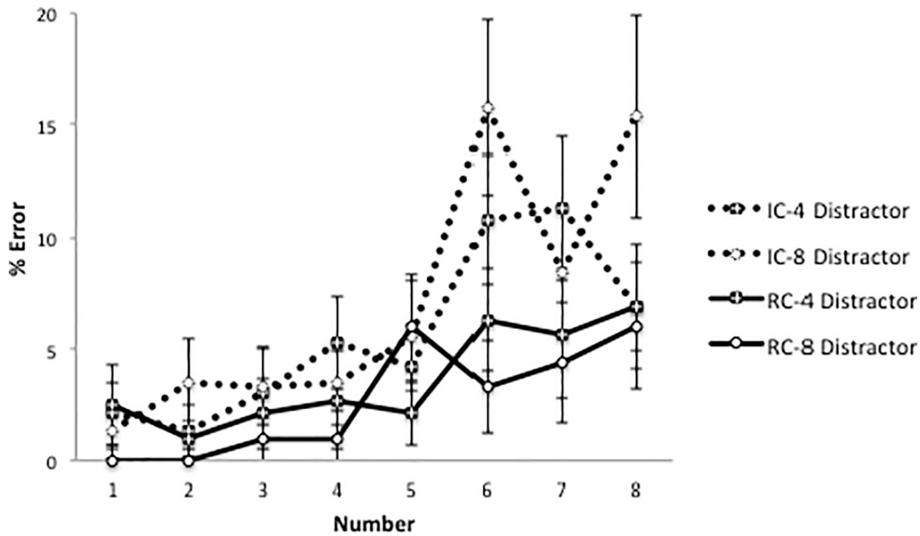


Fig. 7. Mean percent error for enumerating 1–8 vertical targets in 4 or 8 horizontal distractors in the selective enumeration task (Experiment 3). IC: Illusory contour figures. RC: Real-contour controls. Standard error bars included.

6. General discussion

These investigations were designed to accomplish two goals, one related to the study of search and the other to enumeration. As it relates to search, this study was intended as a conceptual replication of the Li et al. (2008) across related tasks. However, this study showed that the results did not replicate across tasks. Although both search and selective enumeration (enumerating targets among distractors) require distinguishing targets from distractors and both can measure distractor costs (the increase in time to process a single item as a function of the number of distractors), the search task revealed no significant difference between distractor costs between line-ending illusory contours and the corresponding real-contour controls (M difference < 2 ms, with real-contours having higher distractor cost though both were extremely close to zero). In contrast the selective enumeration revealed, a difference of over 110 ms, with illusory contours yielding substantially higher distractor costs as shown in Fig. 9.

It's not too surprising that distractor slopes were higher in selective enumeration than search. Enumerating a single target with accuracy would require that the participants check all of the distractors to ensure there was no additional targets, and that would require exhaustive search. Consequently, there is reason to expect that there might be a relationship between target absent slopes in search, and in fact, in this study, for real-contour controls, the distractor cost to enumerate a single item were 30 ms/distractor, about twice the target absent slope observed in our search pilot for the real-contour controls (see Table 1). However, for the illusory contour figures, the distractor costs were

Table 3

Experiment 3: Enumeration RT slopes in milliseconds per target for the 1–3 and 6–8 item ranges in the selective enumeration task with vertical targets in 4 or 8 horizontal distractors. Real control controls and line-ending illusory contours compared. Standard errors listed in parentheses. Note: RT slopes in enumeration studies mean the increase in RT with each additional target to enumerate.

Number of distractors		Real contour figure	Illusory contour figure
Four	1–3 target range	104.75 (39.11)	302.87 (32.22)
	6–8 target range	374.81 (60.11)	312.10 (31.77)
Eight	1–3 target range	189.68 (45.04)	226.96 (53.55)
	6–8 target range	325.10 (27.89)	173.35 (48.43)

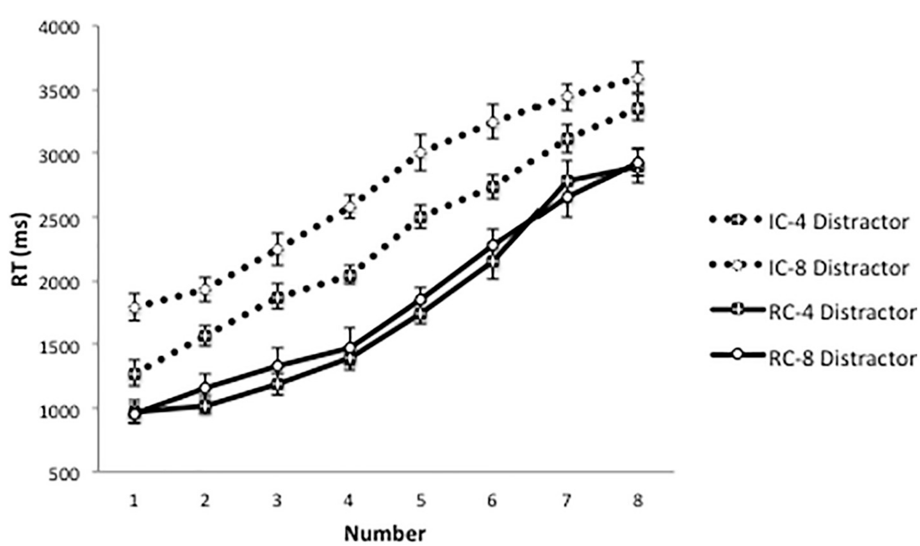


Fig. 8. Mean enumeration response time (RT) in milliseconds for enumerating 1–8 vertical targets in 4 or 8 horizontal distractors in the selective enumeration task (Experiment 3). IC: Illusory contour figures. RC: Real-contour controls. Standard error bars included.

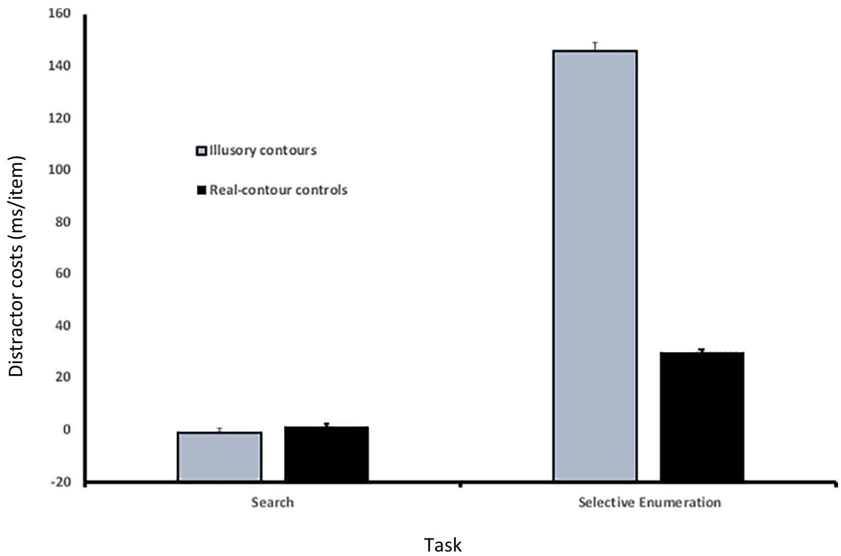


Fig. 9. Mean cost per distractor in milliseconds when there is a single target in a visual search task (Experiment 1) as compared to a selective enumeration task (Experiment 3). Standard error bars included.

almost 10 times those of the corresponding target absent slopes in search. It is clear that the relationship between distractor costs in search and selective enumeration are very different for illusory contours than the corresponding real-contour controls. There was nothing in the search performance that would predict the large discrepancy in distractor costs between real and illusory contours seen in selective enumeration, a difference that emerged even when there was only a single item to enumerate and the displays were identical to those used in search.

The discrepant patterns of performance in search and selective enumeration could indicate one of two things. One is that the standard search task is subject to floor effects that masked the differences between real and illusory contours (in both cases search slopes were close to zero). The standard search task may be too quick and easy. Despite the immense variation slopes, performance is still divided into two categories: inefficient and efficient or more or less attention demanding (e.g. Wolfe, 1998). This might be partially remedied by using search tasks in combination with selective enumeration. Using these tasks in combination may reveal three categories: cases where distractor costs are relatively low in both search and selective enumeration (e.g., real-contour controls); cases where distractors costs are relatively high in both search and selective enumeration; and cases where distractor costs are relatively low in search but high in selective enumeration (e.g. the line-ending illusory contour figures).

Nonetheless, it is also possible the discrepancies in distractor costs between search and selective enumeration occur because these tasks require slightly different things of the participant. Consequently, one task may bring to light differences in conditions that are impossible to see in the other. For example, over the years, there has been controversy about whether the standard search task actually requires determining the location of the targets, particularly when search is efficient (e.g., Duncan & Humphreys, 1989; Eckstein, Thomas, Palmer, & Shimozaki, 2000; Hulleman & Olivers, 2017; Treisman & Gelade, 1980; Wolfe, 1994, 2007). It is possible that efficient search is accompanied by localization in some situations and not others. If participants achieved efficient search for real-contour figures by localizing targets and efficient search for line-ending illusory contours by global using homogeneity/heterogeneity, it is possible that the differences between real and illusory contour figures would only reveal themselves is in tasks that require target localization. Selective enumeration is such a task. For accurate enumeration, target localization is necessary in the first initial moment of presentation because the only way to distinguish one target from another in static displays is by location. In this way, selective enumeration may reveal differences between the real and illusory contours that were not evident from the distractor costs in search.

However, even without distractors, there may be differences between real and illusory contours though in our study this effect was more evident with small numbers than large. In simple enumeration (Experiment 2), although the main effect of figure was not statistically significant across the number range (1–8), on average participants were 65 ms slower to enumerate illusory contours than the real-contour controls. This effect of figure type was statistically significant at 1 item (M difference = 70–80 ms) but disappeared once there were 7 or 8, obscured perhaps by the statistical noise associated with the various different operations necessary for counting larger numbers of items (mental addition, marking areas off as enumerated so items are not enumerated twice, making eye movements). In absence of distractors or even other items in the display, overall RT differences between real and illusory contours might occur if these figures varied in terms of some global (parallel) factor rather than one that affected one area at a time. This might occur if illusory contour figures (items defined by disconnected dots) were somehow harder to see – or alternatively, if seeing an illusory contour figure required grouping operations that take time but nonetheless operate in parallel across the image (Koffka's, 1935 first stage). If these operations occur in parallel all across the image, that means it would not affect RT slopes in search. It is as if the initial low level processing of the items were delayed, but once a sufficiently clear representation was accomplished, there were no further delays in spatially serial stages of analysis. Because the difference emerged even in simple enumeration when there was no need to distinguish between items based on their shape (vertical versus horizontal) this suggests that the main effect did not reflect time required to distinguish targets from distractors (Koffka's second stage).

6.1. Implications for the study of enumeration

Even though the displays crowded (a textured background of diagonal lines), this study revealed evidence of subitizing and counting in items defined by line-ending illusory contours as well as the corresponding real-contour controls in simple enumeration (Experiment 2). This result would be hard to explain based on theories that propose that subitizing only occurs when contour density is low (e.g. Atkinson et al., 1976) or when individual dots can be aligned to form a shape (Mandler

& Shebo, 1982; 1 dot = a point; 2 dots equal a line; 3 dots = a triangle; 4 dots = a square) given that the vertical and horizontal bars themselves were defined by disconnected edge points.

This study also showed evidence that subitizing occurred even in selective enumeration, as would be consistent with the attention based theory of enumeration (Trick & Pylyshyn, 1994). Distractor costs in selective enumeration dictated whether or not subitizing and counting was evident from target RT slopes. When distractor costs in selective enumeration were relatively low, as occurred with the real-contour controls, there was also evidence of subitizing in the RT discontinuities between small and large numbers of targets; RT slopes in the 1–3 target range were significantly lower than the corresponding slopes in the 6–8 range. In contrast, for the illusory contour figures, where the distractor costs were high in selective enumeration there was no evidence of subitizing and counting. There is no evidence of differential processing of small (subitizing) in cases where finding a single item among distractors in itself require the one-area-at-a-time processing associated with moving an attentional focus from one place to the next.

However, it is at this point that we encounter a problem in the argument. At present, it is unclear what constitutes a low distractor cost in selective enumeration. It is reasonable to expect that distractor costs might be higher in selective enumeration than in the corresponding search task because participants had to be sure there were no other targets before they make a numeric response, and this would involve going through the full display before responding. Nonetheless, there is no agreed upon criterial value in selective enumeration to indicate the involvement of attention. In contrast, there is an explicit criterion in the search literature, an arbitrary rule that has developed over the years: attentional requirements are deemed to be minimal when distractor costs are < 10 or 20 ms/distractor (see Li, Cave, & Wolfe, pg. 474, 484). The advantage of using distractor costs from search tasks is that they have an agreed upon criterion for distinguishing between more or less attention-demanding search (inefficient and efficient search). Unfortunately, as can be seen from the results of this study, distractor costs in search are not necessarily the best predictors of distractor costs in selective enumeration let alone whether or not there is evidence of subitizing as shown by discrepancies in target RT slopes between 1–3 and 6–8 targets.

In past, distractor costs in search have been used to test predictions of whether or not subitizing will occur in selective enumeration. However, this has resulted in inconsistencies in the literature that make it difficult to make headway in testing theories – or at least an attention-based theories. For example, there are cases when efficient search predicts subitizing in selective enumeration, as occurred with the real-contour controls in this study. Efficient search also predicts subitizing in selective enumeration when the items are presented against a blank background and participants are enumerating vertical targets in horizontal distractors, white targets in green distractors, or O's in X's in young adults (e.g., Maylor et al., 2011; Trick & Pylyshyn, 1993; Watson et al., 2002), diamonds figures among squares (e.g. Trick & Enns, 1997a), and downturned curves in flat lines (Watson & Blagrove, 2012). Low distractor costs in search also predict low RT slopes in the subitizing range for targets different from distractors in terms of large and small differences in brightness, and large discrepancies in line length (Trick & Enns, 1997b).

Conversely, there are also case where there is inefficient search (high distractor costs) and no evidence of subitizing in selective enumeration, as occurs when participants are enumerating O's in Q's (Trick & Pylyshyn, 1993, 1994; Watson et al., 2005), white vertical targets in green vertical and horizontal bars (Trick & Pylyshyn, 1993, 1994) or when targets or distractors were un-shaded cubes differing in three-dimensional orientation, or two-dimensional diamond shapes where the white quadrant was on the top as compared to the bottom of the figure (Trick & Enns, 1997b).

However, there are also situations where there are low distractor costs in search and no evidence of subitizing, as occurred for the line-ending illusory contours in this study. Similarly, search is efficient for negative schematic faces among neutral (Eastwood, Smilek, & Merikle, 2001) but there is no evidence of subitizing in selective enumeration of negative faces in neutral faces (Watson & Blagrove, 2012). Distractor costs are low when older adults search for an O among X distractors, and yet, there is no evidence of subitizing when they enumerate O's in X's (e.g. Watson et al., 2002). Search for red targets among green is efficient even when the targets are reddy-brown and the distractors are olive green and fairly similar in terms of their colour based on Commission Internationale de l'Eclairage (CIE) 1976 u' v' color space but there was no evidence of subitizing in selective enumeration involving these items (Watson et al., 2007).

Thus, whether it is due to floor effects in search or strategy differences between search and selective enumeration, distractor costs as measured in search are an unreliable predictor of whether or not there is evidence of subitizing in selective enumeration. It would probably be better to use distractor costs as measured in selective enumeration as a predictor of subitizing but the difficulty here is that although the selective enumeration tasks are becoming increasingly common in the literature (e.g. Ester et al., 2012; Pagano & Mazza, 2012; Tollner, Conci, Muller, & Mazza, 2016; Watson et al., 2002, 2005, 2007; Watson & Blagrove, 2012; Watson & Maylor, 2006) most do not report distractor costs as it affects time to enumerate a single item because they do not manipulate the number of distractors. It is possible that subitizing and counting only occur with certain numbers of distractors or certain types of item in selective enumeration– but it will be impossible to observe this if distractor costs in selective enumeration are not reported. In particular, it is important to make note of any discrepancies in distractor costs as measured in search and selective enumeration, such as the ones shown in this study.

6.2. General conclusion

Overall, this study illustrates the benefits of conceptual replication using related paradigms. Real and illusory contours were used as an example but these findings may provide a general cautionary note those using the results of standard search tasks to make inferences about the attentional demands in other tasks that might require finding targets among other items in a display. For example, the literature on search is now being applied to understand performance in a variety of real-world tasks such as technicians searching for tumours on X-rays or security personnel search for guns and explosives (Biggs, Kramer, & Mitroff, 2018; Mitroff, Ericson, & Sharpe, 2018; Van Der Gijp et al., 2017). This study suggests that it may be risky to assume that the results of a standard search task will necessarily replicate in other contexts. This is particularly true given that these applied tasks routinely require actual target localization rather than mere judgements of target presence or absence. For example, for X-ray technicians it is not only important to know that there is a tumour but where that tumour is on the X-ray. Similarly, security personnel not only need to that someone in the crowd has a gun, but they need to know where that person is. Moreover, as in enumeration, both of these tasks require the ability to respond differentially to the presence of more than one target. There may be more than one tumour, more than one individual carrying a gun. That is why conceptual replications such as this one may be useful before assuming the results of search will generalize to other tasks.

Declaration of Competing Interest

None.

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