Enumeration of Illusory Contour Figures

by

Natasha Dienes

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Visual search and enumeration tasks were used to assess the attentional demands of processing illusory contour figures (figures composed of contours that are perceived despite there being no physical changes in the scene). In all tasks, participants were required to find or enumerate a vertical rectangle(s) defined by either line-endings or “pacmen” figures (Kanizsa class). Search time for line-end class figures did not increase markedly as the number of horizontal distractors increased (efficient search). In contrast, when searching for Kanizsa targets amid horizontal distractors, search was inefficient. Simple enumeration (enumeration of targets) and selective enumeration (enumeration of targets in distractors) tasks were used to disambiguate two stages of figure processing: individuation and shape discrimination. Specifically, simple enumeration was used to assess the attentional demands of unit formation and individuation (defining a unit as unique and separate from everything else) of the objects and selective enumeration measured the attentional demands required to discriminate target shapes from distractor shapes. Participants enumerated 1-9 vertical real or illusory contour rectangles either without distractors or with 4 or 8 horizontal distractors. Subitizing, a fast (40-100 ms/target) process specialized for small numbers of items (e.g. 1-3), is only evident when enumeration makes low attentional demands; when attentional demands are greater, the same slow process is used throughout the number range (e.g. 200+ ms/target in the 1-8 range, Trick & Pylyshyn, 1994). Both line-end and Kanizsa class real and illusory contour figures were subitized in simple enumeration, indicating that
individuation of these figures is not attentionally demanding. However, subitizing was only evident for line-end real-contour figures in selective enumeration. This suggests that attention plays a role in defining shapes formed by illusory contours. These findings contribute to our understanding of both illusory contours and enumeration.
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# Table of Contents

Abstract .......................... ii
Acknowledgements ................ iv
List of Tables ..................... ix
List of Figures ................... x
Introduction ....................... 1
  Illusory Contours ................ 1
  Stages of Visual Processing ...... 4
  Behavioural Methods of Studying Visual Processing . 5
    Visual Search .................. 5
    Visual Enumeration ............. 7
Current Experiments ............. 10
Line-end Figures .................. 11
  Experiment 1 (Visual Search) ... 11
    Method ........................ 11
      Design ........................ 11
      Participants .................. 12
      Materials .................... 12
      Procedure ................... 13
Results ........................... 14
  Error Rate ...................... 14
  Reaction Time ................... 15
  RT Slope ......................... 15
Experiment 2 (Simple Enumeration) 16

Method 16

Design 16

Participants 16

Materials 17

Procedure 17

Results 18

Error Rate 18

Reaction Time 19

Enumeration RT Slope 19

Experiment 3 (Selective Enumeration) 20

Method 21

Design 21

Participants 21

Materials 21

Procedure 21

Results 22

Error Rate 22

Reaction Time 22

Distractor RT Slope 23

Enumeration RT Slope 24

Discussion Experiments 1-3 25

Kanizsa Figures 26
Experiment 4 (Visual Search) 26
Method 26
Design 26
Participants 26
Materials 27
Procedure 27
Results 27
Error Rate 28
Reaction Time 28
RT Slope 28

Experiment 5 (Simple Enumeration) 29
Method 30
Design 30
Participants 30
Materials 30
Procedure 30
Results 30
Error Rate 31
Reaction Time 31
Enumeration RT Slope 31

Experiment 6 (Selective Enumeration) 31
Method 33
Design 33
List of Tables

Table 1. Search reaction time (RT) slopes, M (SE), in ms/item for the line-end class figures from Experiment 1 and from Li, et al. (2008).

Table 2. Enumeration reaction time (RT) slopes in ms/item, M (SE), for 1-3 and 6-8 target ranges in the simple enumeration task (Experiment 2).

Table 3. Enumeration reaction time (RT) slopes in ms/item, M (SE), for 1-3 and 6-8 target ranges in the selective enumeration task using line-end class stimuli (Experiment 3).

Table 4. Search reaction time (RT) slopes, M (SE), in ms/item for the Kanizsa class figures from Experiment 4 and from Li, et al. (2008).

Table 5. Enumeration reaction time (RT) slopes in ms/item, M (SE), for 1-3 and 6-8 target ranges in the simple enumeration task (Experiment 5).

Table 6. Enumeration reaction time (RT) slopes in ms/item, M (SE), for 1-3 and 6-8 target ranges in the selective enumeration task using Kanizsa class stimuli (Experiment 6).
List of Figures

Figure 1. Illusory contour figures. (a) Kanizsa illusory contour rectangle on the left. (b) Line-end illusory contour rectangle on the right.

Figure 2. Real contour figures. (a) Kanizsa real contour rectangle on the left. (b) Line-end real contour rectangle on the right.

Figure 3. An example of a simple enumeration task for line-end illusory contour figures. In this figure, there are two targets.

Figure 4. An example of a selective enumeration task for line-end illusory contour figures. In this figure, there are two targets (vertical rectangles) and four distractors (horizontal rectangles).

Figure 5a. Mean error rates in percentages for both types of line-end class figures for target present and target absent trials in the visual search task (Experiment 1).

Figure 5b. Mean reaction time (RT) in ms for both types of line-end class figures for target present and target absent trials in the visual search task (Experiment 1).

Figure 6a. Mean error rates in percentages for each type of line-end class figure for each number of targets in the simple enumeration task (Experiment 2).

Figure 6b. Mean reaction time (RT) in ms for each type of line-end class figure for each number of targets in the simple enumeration task (Experiment 2).

Figure 7a. Mean error rates in percentages for line-end class figures for each number of targets and distractors in the selective enumeration task (Experiment 3).

Figure 7b. Mean reaction time (RT) in ms for line-end class figures for each number of targets and distractors in the selective enumeration task (Experiment 3).
Figure 8a. Mean error rates in percentages for both types of Kanizsa class figures for target present and target absent trials in the visual search task (Experiment 4).

Figure 8b. Mean reaction time (RT) in ms for each type of Kanizsa-class figure for target present and target absent trials in the visual search task (Experiment 4).

Figure 9a. Mean error rates in percentages for each type of Kanizsa-class figure for each number of targets in the simple enumeration task (Experiment 5).

Figure 9b. Mean reaction time (RT) in ms for each type of Kanizsa-class figure for each number of targets in the simple enumeration task (Experiment 5).

Figure 10a. Mean error rates in percentages for Kanizsa class figures for each number of targets in the selective enumeration task (Experiment 6).

Figure 10b. Mean reaction time (RT) in ms for Kanizsa class figures for each number of targets in the selective enumeration task (Experiment 6).

Figure 11. A summary of the findings from the three different paradigms and the processes associated with each, for each type of figure.
Enumeration of illusory contour figures

In this study I am investigating illusory contours (lines that are perceived even though there are not actual differences in brightness or colour in the image) and I am using the enumeration task (the task of determining the number of items in the display) in order to shed light on the type of processing that is used to derive contours. Illusory contours are important because we live in a 3-dimensional world where things move, go behind other things and disappear into shadows. The edges that define the form of the object are sometimes obscured. Yet, we are still able to perceive those things, to recognize and name them, and to coordinate our bodies so that we can touch or avoid these objects, even though the differences in brightness or colour that typically define the object contours are not present in the image. We can use illusory contours and their induced figures to study the way our visual system accomplishes this task. In the sections that follow I first discuss illusory contour figures (also known as subjective figures), then I will discuss the stages of visual processing. I will follow this discussion with an explanation of the behavioural methods that are used to study the stages of visual processing (visual search and enumeration). I will end with a description of the present studies.

*Illusory Contours*

Illusory contours are unusual in that they are not defined in the same way as the physical contours that surround other objects. Physical contours are perceived due to a sudden change in luminance or colour in the visual scene. Frequently, however, a portion (or portions) of an object’s physical contour is not available to the visual system. There are two scenarios that may lead to this missing information. The first occurs when an object is behind something. This is called occlusion. When an object is occluded, the visual system is able to fill in the missing portions of contour via a process that has been termed amodal completion. The second reason a
portion of the physical contour surrounding an object may not be visible occurs when an object is in front of a background that has the same properties as itself (i.e., the object and background are homogeneous). In this situation the visual system fills in the missing contours with a process called modal completion. Illusory contours are perceived as a result of modal completion (Driver, Davis, Russell, Turatto & Freeman, 2001; Halpern, 1981; Kanizsa, 1979; Shipley & Kellman, 1992; Singh, 2004).

Illusory contour objects are objects that are defined by illusory contours (Figure 1). When these objects are perceived, they are seen to occlude the surfaces that induce them and are also seen as brighter than the background, even though the contour exists across a homogeneous area (Kanizsa, 1979). A Kanizsa illusory contour figure (Figure 1a) is composed of circles with “bites” taken out of them that form the corners of the figure (Kanizsa, 1976; 1979). I will call these inducing corners “pacmen”, after the videogame figures of the same shape. The illusory contours extend out from the lines of the pacmen’s “mouths”, forming an illusory shape. In contrast, line-end illusory contour figures (Figure 1b), as the name suggests, are induced by lines or stripes that have been cut off. The ends of these stripes, or lines, induce the contours that define the figure (Gurnsey, Humphrey & Kapitan, 1992; Lesher & Mingolla, 1993; Li, et al., 2008).

Understanding how the visual system defines illusory contours is important because these contours are what the visual system uses to define objects as wholes. This defining process is important for both object recognition and visual motor coordination. Many researchers have recognized this importance and contributed research to this fascinating topic (e.g., Barlasov-Ioffe & Hochstein, 2008; Halko, Mingolla & Somers, 2008; Halpern, 1981; Kanizsa, 1976; 1979). A wide range of theories have been put forth attempting to explain how we perceive these odd
objects. One theory postulates that perceived brightness contrasts are responsible for the formation of illusory contours (although see Kanizsa 1979 for a discussion of why brightness contrast is a consequence and not a cause of illusory contours). Another theory is that depth cues allow the visual system to segregate illusory contour objects from their backgrounds. It has also been theorized that illusory contour figures are formed by the activation of orientation-specific neurons. According to this theory, if enough neurons corresponding to a single orientation are activated all at once in close enough proximity, they will be “linked” together to produce the illusory contour (Grossberg & Mingolla, 1985; see Halpern & Salzman, 1983 for evidence for and against each of these theories).

Other researchers have been interested in factors that lead to a stronger perception of illusory contours (e.g., Reynolds, 1981). For example, Lesher and Mingolla (1993) varied the number of inducing lines and their thicknesses and asked participants to rate the strength of the perceived figure for each combination. There has also been interest in a possible shared mechanism used to perceive both occluded and illusory contour objects (Kalar et al., 2010; Shipley & Kellman, 1992; Singh, 2004).

There are a variety of ideas about how illusory contours are derived, but it is important to know the extent to which attentional resources are required to derive these contours, especially when one considers the influence of attentional demands on object recognition and visual motor coordination. Despite the vast amount of research and interest devoted to illusory contours, few researchers have explored the extent to which attentional resources are required to process illusory contours. We therefore ask: At what stage in the visual processing stream of attention are illusory contour figures processed?
Stages of visual processing

A classical view of the stages of visual processing is that visual processing is divided into two stages. The first is the preattentive stage. This stage is capacity unlimited because the visual system is able to pick up all the information in the visual field. It is also spatially parallel because information from the entire visual field is processed together (Treisman & Souther, 1985; Treisman & Gelade, 1980; Wolfe, Cave & Franzel, 1989). In the preattentive stage, the visual system segregates visual information on the basis of simple features such as colour, brightness, orientation and direction of movement (Cavanagh, Arguin & Treisman, 1990; Nakayama & Silverman, 1986; Treisman & Gelade, 1980; Treisman & Souther, 1985). The second stage is called the attentive stage. This stage is capacity limited, meaning that only a small amount of visual information can be processed at once. It is also spatially serial, which means that the visual system has to move to one area or object at a time to process the information. In the attentive stage, information is processed according to goals based upon features that were obtained in the preattentive stage. For example, if your task was to find a particular vertical rectangle, then you would process visual information according to an orientation-based goal (a preattentively identifiable feature).

However, there have been some developments in this theory since (e.g., Li, Cave & Wolfe, 2008; Wolfe, 1998). A vast amount of research has indicated that searches cannot be divided into the strict dichotomy of parallel and serial. Instead we can compare search slopes to one another to determine if some are more or less efficient than others (Wolfe, 1998). Nonetheless, the idea remains that some object distinctions can be accomplished quickly or more efficiently than others, before the serial processing of attention, while others need more time and attention to
identify. We can study these stages of visual processing using several different behavioural methodologies.

**Behavioural methods of studying visual processing**

**Visual search**

One classic tool for studying the stages of visual processing is the visual search paradigm. A typical visual search task requires a participant to find a target item in a display of distractor items, and the reaction time (RT) is measured. The attentional demands of a particular search are assessed by calculating the RT slope (the increase in RT per distractor). If the RT slope is relatively flat (typically 10 ms/item or less), then the search is considered efficient (e.g., Treisman & Souther, 1985; Wolfe, 1998). If the RT slope is steep (> 20 ms/item), and the slope for the target absent trials is approximately twice that of the target present trials, it is considered an inefficient search (e.g., Wolfe, 1998).

Efficient search is generally referred to as “pop out” search, as the target items seem to “pop out” from the distractors in the display and is associated with efficient search that can be accomplished without the use of attention (e.g., Treisman & Souther, 1985; Nakayama & Silverman, 1986; Wolfe, 1998). Inefficient search is thought to be conducted with the use of attention (e.g., Treisman & Souther, 1985; Nakayama & Silverman, 1986; Wolfe, 1998). Efficient visual search generally occurs when the target differs from its surrounding distractors by a single, preattentively identifiable feature, such as colour (Nakayama & Silverman, 1986), orientation, shape, etc. (Treisman & Gelade, 1980). Inefficient search occurs if, for instance, a target is distinguished from the distractors by a conjunction of features. An example of this would be a white horizontal bar that has to be found amongst white vertical bar and black horizontal bar distractors (e.g., Treisman & Souther, 1985).
Gurnsey, Humphrey and Kapitan (1992) used visual search to study line-end illusory contour figures (figures induced by line ends). Their paradigm required participants to perform a visual search for a vertical line-end illusory contour bar among horizontal line-end illusory bars. They found that search was efficient, indicating that an orientation-based search for the vertical line-end illusory contour bar could be performed before attention. Li, Cave and Wolfe (2008) followed up on this study and also found that search for a horizontal line-end illusory contour figure amid vertical line-end illusory contour figures was efficient. Additionally, they found that an orientation-based search for figures composed of the line-end inducers and a real contour rectangle was also efficient. Thus, there is evidence that the processes involved in defining illusory contours based on line ends does not require the slow and potentially even “one area/item at a time” processing associated with attentional processing.

In contrast to the studies using line-end class figures, Grabowecky and Treisman (1989) set up a visual search task wherein participants were asked to find a Kanizsa style illusory contour triangle (a triangle induced by pacmen). The distractors in the array were pacmen inducers in sets of three that were rotated so as not to induce an illusory shape. They found that search for a Kanizsa triangle was inefficient in this situation, indicating that Kanizsa triangles were processed in the attentive stage. Li, Cave and Wolfe (2008) followed up on this study using visual search for a Kanizsa illusory contour rectangle based on orientation. They found that when participants were asked to find a horizontal Kanizsa rectangle presented with vertical Kanizsa rectangle distractors, search was inefficient. However, they found that an orientation-based search for a figure composed of the Kanizsa pacmen inducers and a real contour rectangle was efficient. Their results also indicate that Kanizsa illusory contour figures need attention to be processed, but that their real-figure counterparts can be processed before attention is allocated.
There is a problem with this conclusion, however. Visual search confounds several stages of visual processing (Trick & Enns, 1997a). In order to complete a visual search task, a target must first be defined as an object. To be defined as an object, the contours of the object must be brought together to form a unit (unit formation). If the task is more difficult, the unit may need to be individuated. The individuation of a unit involves defining a unit as an individual, separate from everything else. Individuation may be a necessary step in a difficult search because when a search is difficult people cannot deal with all of the items in a scene at once (hence the relatively large RT slope with the number of distractors in search). Instead they are forced to process the scene one or a few items at a time (Treisman, & Gelade, 1980). If a search is being conducted by processing one or a few items at a time, it is essential to distinguish between items that are currently attended, those that have already been processed, and those that have yet to be processed to successfully complete the task. This means that items (units) need to be individuated so that the items that have been already examined are perceived as separate from ones that have not already been searched through. After the units have been formed (and individuated if necessary), the targets must be discriminated from distractors based on their respective feature(s). In order to better understand the attentional demands processing illusory contour figures, the attentional demands of individuating a figure can be separated from the attentional demands of discriminating target shapes from distractor shapes with a different paradigm: enumeration.

**Visual enumeration.**

In a visual enumeration experiment, participants are presented with an array and asked to determine the number of targets present. In a simple enumeration task, only targets are presented (see Figure 3). This type of task requires only unit formation and individuation. Individuation is
critical in enumeration tasks because it is necessary to distinguish between items that have already been enumerated from those that have not; items must be enumerated once and only once. It is also necessary to ensure that the entire unit is enumerated as “one” and not a part of that unit or a combination of parts of units. In a simple enumeration task there is no need to discriminate between target and non-target objects. Therefore, the level of processing that is required to define and individuate an object can be assessed by analyzing the RT and accuracy in a simple enumeration task. The pattern of accuracy and RT dictates what type of enumeration was required for that task (Trick, 2008; Trick & Enns, 1997a; Trick & Enns, 1997b; Trick & Pylyshyn, 1993; 1994).

There are two patterns of response that can emerge for accurate enumeration. The first is subitizing. Subitizing is characterized by a fast (40 - 100 ms/item) and very accurate enumeration of a small number of items (3-5 on average; Trick & Pylyshyn, 1993; 1994). The second pattern of response is counting. Counting is a slow process (250 – 350 ms/item) and is less accurate than subitizing. Subitizing and counting have been shown to be two separate enumeration processes. For example, when items are heterogeneous in a display, and participants are lead to expect that about half are of one type and half are the other, slopes increase but counting slopes decrease (Trick, 2008). In addition, Dehaene and Cohen (1994) found that simultagnosia patients were able to accurately enumerate a small number of items, but they were not able to enumerate more than three items. In other words, simultagnosia patients retained their ability to subitize but not their ability to count. It has also been demonstrated that the pattern of event related potentials (ERPs) is different for subitizing and counting (Nan, Knösche & Luo, 2006). This dissociation in effects from subitizing and counting indicates that subitizing and counting must be governed by different mechanisms.
When accuracy is high, the difference between subitizing and counting is determined using the RT slopes for a small (1-3) number of objects as compared to a larger (6-8) number of objects. If the RT slope for the large number of items is significantly higher than the RT slope for the small number of items, it can be assumed that a different enumeration process is being used for each number range; this in turn indicates that the small number of items were subitized and the larger number of items were counted. If the RT slope for both ranges are high (i.e., not significantly different), then it can be assumed that counting is needed to enumerate all number of items in that situation (Trick, 2008; Trick & Pylyshyn, 1993; 1994).

The dichotomy between the pattern of responses for subitizing and counting in a simple enumeration task tells us what level of processing is required to individuate an object. If the pattern of results indicates that the array has been subitized in a simple enumeration task, then it is concluded that the definition of items as wholes and the individuation of the items in that array occurs without the need for one-area-at-time attention. If an array of items must be counted in a simple enumeration task, this indicates that attention is needed to individuate these items to ensure items are not missed or enumerated twice; this occurs when there are more items than can be individuated at one time.

The patterns indicative of subitizing and counting can also be used to assess the level of processing that is required to discriminate targets from distractors. This is measured using a selective enumeration task (see Figure 4). A selective enumeration task combines a simple enumeration task with a visual search task. Participants are instructed to selectively enumerate only the target items in the display and ignore the distractors. Targets must be both individuated from one another and discriminated from distractors in order for a selective enumeration task to be completed successfully. The pattern of results that emerges can therefore tell us what level of
processing is needed to discriminate the targets from the distractors. If the targets are subitized in a selective enumeration task, then it may be concluded that the discrimination of targets from distractors occurs without the need for attention. That is, if there is a difference in the RT slope in the enumeration task between small and large numbers of items, then distinguishing between the targets and distractors does not require attention. If targets are counted even when there are only small numbers of targets, they are discriminated from distractors using attention (in this case there should be no evidence of differences in RT slope between small and large numbers of items).

Because both visual search and selective enumeration tasks present targets with distractors, it is logical that both should assess similar things, and there is empirical evidence that they do. Most items that pop out in visual search can also be subitized in a selective enumeration task. For example, if the visual search task is to search for the vertical target amid horizontal distractors, search is efficient. Likewise, if the selective enumeration task is to enumerate the vertical targets when they are presented with horizontal distractors, the targets can be subitized (Trick & Enns, 1997b). In addition to orientation of objects, differences in brightness, length and colour between target(s) and distractors result in both efficient search and subitizing. Additionally, arrays that would lead to an inefficient search where RT increases with the number in the display such as search for targets that are defined by a conjunction of features (e.g., brightness and orientation), require counting in order to be enumerated in a selective enumeration task (Trick & Enns, 1997b). Based on this evidence, one should come to the same conclusion about the attentional demands of discriminating targets from distractors using either paradigm. That is, there should be no evidence of subitizing when discriminating targets from distractors (the differences in RT
slope between small and large numbers of items indicative of subitizing should not be present) when search is inefficient, but there should be evidence of subitizing if search is efficient.

Current experiments

This series of experiments used line-end illusory contour rectangles and Kanizsa illusory contour rectangles to provide a more detailed picture of how illusory contour figures are processed by distinguishing between the attentional demands of individuating an illusory contour figure (simple enumeration) and the attentional demands of discriminating an illusory contour figure target from distractors (selective enumeration). Because the results from previous experiments (Grabowecky & Treisman, 1989; Gurnsey, et al., 1992; Li, et al., 2008) have shown that the attentional demands of processing these two classes of figures differ, they will be discussed separately. Thus, to begin, I will focus on line end illusory contour figures, and will start with a visual search study to ensure that the figures used in this series of experiments match those used in previous visual search studies and then continue on to studies involving simple and selective enumeration. Then in the next experiments I will focus on the Kanizsa illusory contour figures, beginning again with the visual search studies and progressing to the simple and selective enumeration.

Line-end Figures

Experiment 1 (Visual Search)

The goal of this study was to replicate the efficient search for both illusory contour figures and real contour figures that has been found in previous visual search work (Gurnsey, et al., 1992; Li, et al., 2008). It was important to ensure that the efficient searches could be replicated with our figures in order to confidently compare the results of our enumeration studies to the visual search literature. To replicate previous work, we used the same procedure and the
same type of real and illusory contour figures presented by Li et al. (2008). This meant that the target was either present or absent amid 4, 6, 8, or 12 distractors in each trial. Because this experiment is very similar to past experiments, we expected to also find that search for real and illusory contour figures was efficient.

**Method**

*Design*

In this experiment we manipulated the presence of the target (for target-present or target-absent trials), the number of distractors (4, 6, 8, or 12) and the type of figure (illusory contour figure or real contour control figure) in the display. We measured the effects these variables had on the error rate, RT and RT slopes. The design was entirely within-subjects.

*Participants*

To determine the number of participants needed in the experiments, an a priori power analysis was conducted using G*Power 3.1.5. We were expecting to find large effect sizes (partial $\eta^2 > 0.14$) and at least a moderate correlation between the variables of interest (as most people are consistently fast and accurate across trials in a given task) in all experiments. Given these parameters, we needed to have at least 15 participants to achieve 95% power. We chose to use the data from 16 participants in each experiment, which ensured that we had adequate power for all of our analyses.

In this and all the following experiments, participants were University of Guelph students recruited from the University of Guelph participant pool through SONA. All students were enrolled in an undergraduate Psychology course at University of Guelph and participated for course credit and had normal or corrected-to normal vision. Sixteen participants (age: $M = 18.5$, $SE = 2.1$; male = 4) took part in Experiment 1.
Materials

All stimuli were presented with a Mac OS 9.2 computer on a Mac desktop monitor. Stimuli were presented using Vscope software at a viewing distance of 70 cm. The stimuli used in the experiments were created to mimic the figures used by Li, et al. (2008). The real and illusory rectangles were 5 mm by 10 mm, subtending 0.41° x 0.82° of visual angle and were presented with a jitter of +/- 5 pixels (0.12° of visual angle). The real contour figures included the inducers for the illusory contour rectangles as well as a 0.05° of visual angle wide black contour (2.46 cd/m²) around the rectangle (Figure 2). The target rectangles were always the vertical rectangles, and the distractor rectangles were always the horizontal rectangles. In each trial, one target (vertical) rectangle was either present or absent and was presented with the same number of distractors as Li, et al. (2008): 4, 6, 8, or 12. Unlike Li, et al. (2008), however, the number of distractors was held constant and not the number of items displayed. The figures were presented in an invisible 7 by 7 grid that subtended 8.53° x 8.53° of visual angle, in which the stimuli were randomly arranged. The minimum distance between rectangles was 0.41° of visual angle.

The line-end induced illusory contour rectangles were formed by presenting a white rectangle on the diagonally striped background. All stimuli were presented against a background grid of black diagonal lines (2.46 cd/m², RGB: 0,0,0) displayed against white (78.79 cd/m², RGB: 256,256,256), which means the contrast was high between white and black areas (94%). The diagonally striped background was composed of alternating black (0.02° VA) and white (0.14° VA) diagonal lines at a 45° tilt. The contrast between the background and figure was 94%. Line-end figures could appear in any row or column of the invisible 7 by 7 grid.

Procedure
In all experiments, participants were given a consent form and orally informed of their roles and rights as a participant in this experiment prior to starting the experiment. Instructions were given to participants to sit comfortably upright in their chair for the duration of the experiment. Participants were instructed to indicate if a vertical rectangle was present in the array on the screen as quickly and accurately as possible. Participants pressed the “z” key to indicate that a target was present or the “,” key to indicate there was no target. Feedback would then appear in the form of a + for a correct answer or a – for an incorrect answer.

Participants completed 15 practice trials and were given an opportunity to ask any questions about the task after these were completed. After the experimenter answered any questions, participants began the experimental trials by pressing a key, whenever they were ready to begin. For each figure type, ten trials were presented for each distractor numerosity for both target-present and target-absent trials (80 trials). Only one type of figure appeared in each block of 80 trials and the order of blocks was counterbalanced.

**Results**

Before beginning the analysis, the data was screened for outliers. Any trial further than 2.5 SDs from the mean of each participant’s data for each figure type, target present/absent and distractor numerosity was dropped. The proportion of trials dropped as outliers in this experiment was 1.6%.

In this experiment we manipulated the presence of the target (present or absent), the number of distractors (4, 6, 8, or 12) and the type of figure (real or illusory) in the display. The effects of these manipulations on error rate, RT and RT slope were measured using 3-way within subjects ANOVAs. In this and the following experiments, a Greenhouse-Geisser
correction for sphericity violations was used in all analyses. Post hocs in all experiments were conducted using one-way ANOVAs with a Bonferroni correction.

**Error Rate**

Overall, participants were made few errors when performing this task, $M = 2.10\%$, see Figure 5a. More errors were made when searching for real contour figures, $M = 2.80\%, SE = 0.40\%$, than illusory contour figures, $M = 1.30\%, SE = 0.50\%$, $F(1, 18) = 6.72, p < 0.05$, partial $\eta^2 = 0.27$, but few errors were made when searching for either type of figure so this was not a concern. The number of targets by number of distractors interaction was also significant, $F(2.67, 47.95) = 3.15, p < 0.05$, partial $\eta^2 = 0.15$, however, none of the error rates exceeded 3.50%, so this was not a concern either and was thus not analyzed further.

**RT**

The typical effect of an increase in RT with an increase in distractors emerged, $F(2.23, 40.08) = 16.05, p < 0.05$, partial $\eta^2 = 0.47$, see Figure 5b. As is also typical of visual search studies, the target absent trials, $M = 627.15\, \text{ms}, SE = 27.44\, \text{ms}$, took longer than the target present trials, $M = 575.59\, \text{ms}, SE = 22.70\, \text{ms}$, $F(1, 18) = 12.79, p < 0.05$, partial $\eta^2 = 0.42$. Unsurprisingly, the interaction between these two variables was also significant, $F(2.20, 39.57) = 10.43, p < 0.05$, partial $\eta^2 = 0.37$, but was not of theoretical interest and was therefore not analyzed further. In contrast to the results of Li, et al. (2008), our experiment revealed that the search for illusory contour figures was, on average, slower than the search for real contour figures, $F(1, 18) = 17.69, p < 0.05$, partial $\eta^2 = 0.50$. No other effects emerged. No firm conclusions about our hypotheses can be made from these findings, however, as the efficiency of search is measured by the RT slope and not the RTs.
**RT slope**

The RT slopes were calculated by conducting a regression with the number of distractors as the predictor and the RT as the criterion for each combination of figure type and number of targets. The RT slope for the target absent trials was higher than the RT slope for target absent trials, \(F(1, 18) = 16.59, p < 0.05, \text{ partial } \eta^2 = 0.48\), as is typical in visual search studies. In line with our hypotheses, there was no effect of figure type or interaction, indicating that the real and illusory contour figures both produced an efficient search. This replicates the results of Li, et al. (2008), see Table 1. Because the results of the previous studies (Gurnsey, et al., 1992; Li, et al., 2008) were replicated with our figures, a direct comparison can be made between the results of the visual search and enumeration studies presented here.

**Experiment 2 (Simple Enumeration)**

In this experiment, a simple enumeration task was used to determine if the unit formation and individuation of illusory contour rectangles requires attention. As previously mentioned, a successful visual search task requires targets to be formed into units, possibly individuated, then discriminated from distractors, whereas in a simple enumeration task only unit formation and individuation of the targets is required. We hypothesize that if a figure can be both formed into a unit (and maybe individuated) and discriminated from distractors without attention, that it will be individuated without attention. If the targets can be individuated without attention, we would expect to see that targets are subitized within the subitizing range, which would be indicated by a significant difference in the slopes between 1-3 targets and 6-8 targets. Visual search studies found that search for both illusory contour figures and real contour control figures was efficient (Gurnsey, et al., 1992; Li, et al., 2008).
Method

Design
In this experiment we used a repeated measures design to study the effects of manipulating the number of targets (1-9) and the type of figure (real or illusory) on error rate, RT, and RT enumeration slope.

Participants
Any participant whose error rate exceeded 30 percent for any number of targets for either type of figure was excluded from the analysis, a method that has been used in previous studies (e.g., Trick, 2008). This was done because we were only interested in assessing accurate methods of enumeration (subitizing or counting) and not inaccurate methods. Specifically, we did not wish to study the inaccurate and fast enumeration process of estimation, as it is thought to engage different processes than subitizing and counting (Piazza, Fumarola, Chinello & Melcher, 2011). Furthermore, only the RT data from accurate trials were analyzed. When participants have error rates in excess of 30% there would be too few RTs to analyze given the number of trials per condition and number of items. Three participants were removed from the analysis due to excessively high error rates (18.75% of the sample, age: $M = 17.67, SD = 0.58$; male = 2). Results were included from 16 participants (age: $M = 18.50, SD = 2.13$; male = 4).

Materials
The materials in this experiment were the same as those used in Experiment 1, except that one to nine target (vertical) rectangles and no distractor (horizontal) rectangles were presented in each trial on the invisible 7 by 7 grid.

Procedure
Participants were instructed to indicate the number of vertical rectangles on the screen as quickly and accurately as possible. A two-step response was used, as has been used in other studies (e.g., Trick, 2008). Participants first responded by saying the total number of targets aloud while simultaneously pressing the space bar on the keyboard to indicate that they had completed enumerating the targets in the display. At this point the display disappeared. Next, participants pressed the same number key on the keyboard as the number they had said aloud so that the accuracy of their response could be electronically recorded. Feedback would then appear in the form of a + for a correct answer or a – for an incorrect answer. The purpose of using this two stage process is to get a more accurate measure of RT. By asking participants to respond (initially) the same way to all trials, the measure of RT was not conflated by the manual processes of choosing the correct number key.

As in Experiment 1, participants completed 15 practice trials before beginning the experimental trials. Eleven experimental trials were presented for each type of figure (real or illusory) and target numerosity (1-9). The two figure types were presented in separate blocks of 99 trials each (11 trials per target numerosity). The order of the blocks was counterbalanced.

Results

The following analyses examined the effects of the number of targets and type of figure on error rate, RT, and enumeration RT slope in a simple enumeration task. Outliers were eliminated by removing trials where RT was more than 2.5 SDs away from that participant’s mean for that specific number of targets and type of figure. In Experiment 2, 1.60% of the trials were dropped for this reason.

The results were analyzed first for error rate, then RT, and finally enumeration RT slope, using 2-way within-subjects ANOVAs. The independent variables corresponded to the type of
figure (line-end illusory contour figure, or line-end real contour control figure) and the number of targets to be enumerated (1 to 9).

Error Rate

Error rate was examined using a 2x9 within-subjects ANOVA. Overall error rate was low, $M = 2.2\%$; $SE = 0.4\%$, indicating that participants were using subitizing or counting and not estimation (a fast but very inaccurate form of enumeration). There was the standard main effect for number of targets, with errors increasing with an increasing number of targets, $F(4.62, 69.29) = 2.41, p < .05$, partial $\eta^2 = .14$, see Figure 6a. The main effect of type of figure and the interaction were not significant, both $Fs < 1.30, ps > .05$.

Reaction Time

RT was examined using a 2x9 within-subjects ANOVA. Predictably, there was a significant main effect of number of targets for the RT analysis, $(F(1.97, 29.41) = 205.31, p < .05$, partial $\eta^2 = .93)$, see Figure 6b. This effect was examined in the enumeration RT slope analysis as we were interested in whether or not the figures had been subitized. The main effect of figure class and the interaction were not significant, both $Fs < 2.04, ps > .05$.

Enumeration RT slope

The enumeration RT slope was analyzed so that the type of enumeration and consequently the attentional demands of the stimuli could be determined. If the RT slope for the small number of targets is significantly lower than the RT slope for the larger number of targets, then the results dictate that the targets were subitized. If the RT slopes for small and large numbers of targets are not significantly different, then the targets had to be counted. In this series of experiments I chose to compare the RT slope between one to three targets and six to eight targets. Four and five targets were excluded as some people are able to subitize up to five, and
some people are unable to subitize four targets (Trick & Pylyshyn, 1994). By excluding these
target numbers, it is more certain that the analyzed ranges included only one type of
enumeration. The nine target trials were excluded as it has been noted that participants
sometimes have a speeded response to the largest number of items presented (Trick & Pylyshyn,
1993).

The enumeration RT slopes were calculated by running a regression with the number of
targets as the predictor and RT as the criterion for the one to three target range and the six to
eight target range for each type of figure. The RT slopes were analyzed using a 2x2 within
subjects ANOVA. There was a significant difference in the RT slopes of targets wherein the
slope for one to three targets was lower than the slope for six to eight targets, $F(1, 15) = 29.50, p < .01, \text{partial } \eta^2 = .66$, see Table 2. Therefore we can say that there was evidence of subitizing
insofar as there were RT slope differences between 1-3 and 6-8 targets. The main effect for
figure class and the interaction were not significant, both $F$s < 2.00, $p$s > .05. Overall, these
results indicate that participants were able to subitize one to three targets for both the illusory
contour figures and real contour control figures in the simple enumeration task. Consequently, it
can be concluded that object definition and individuation occurred before attention for both these
types of figures.

**Experiment 3 (Selective Enumeration)**

The goal of Experiment 3 was to examine the attentional demands of line-end illusory
contour targets from distractors by using a selective enumeration task. To achieve this, two types
of RT slopes were calculated to assess the attentional demands of discriminating targets from
distractors. Two distractor numerosities (4 or 8) were presented so the effect of an increase in the
number of distractors could be calculated. Specifically, we looked at how the number of
distractors affected the amount of time required to enumerate a single target (the equivalent to a target present trial in terms of the appearance of the displays). This distractor RT slope for one target will be comparable to the target-present RT slope calculated in visual search studies. As in the simple enumeration task, the effect of an increasing number of targets (enumeration RT slope) was calculated to determine the type of enumeration used.

Visual search studies have found that search for line-end illusory contour figures and their controls are efficient. We hypothesize that the results of this study will also find evidence from both types of slopes that discriminating line-end illusory and real contour targets from distractors does not require attention. We therefore expect to see a difference for both real and illusory contour figures between the enumeration RT slopes of the one to three target range and the six to eight target range, indicating that the figures were subitized. We also expect that the distractor RT slope will be low for both types of figures.

**Methods**

*Design*

This experiment was conducted entirely within subjects. The independent variables manipulated in this experiment were the number of targets (1 to 9), the number of distractors (4 or 8) and the type of figure (real or illusory). The effect of these manipulations on error rate, RT, and enumeration RT slope was analyzed.

*Participants*

Ten participants were dropped as their error rates were higher than 30 percent (38.46% of the sample, age: $M = 18.60, SD = .52$; males = 0). The unfortunately high attrition rate was due to many participants not following instructions properly in an effort to finish faster, as it was the
end of the semester. Data from 16 participants with normal or corrected-to normal vision were used in the analyses (age: $M = 19.13$, $SD = 1.45$; males = 8).

**Materials**

The materials used in Experiment 3 were the same as those used in Experiment 2 except that four or eight distractors (horizontal rectangles) were presented with the targets (vertical rectangles) in each trial (see Figure 4).

**Procedure**

The procedure for Experiment 3 was the same as the procedure for Experiment 2 with the following exceptions. Two blocks of 50 trials were presented for each type of figure (real contour rectangles and illusory contour rectangles), making a total of 100 trials for each of the two types of figures.

**Results**

This experiment examined the effects of the number of targets, number of distractors and type of figure on error rate, RT, and enumeration RT slope in a selective enumeration task. The outlier RTs were dropped by removing trials that were 2.5 SDs or more from that participant’s mean for that type of figure, number of targets and number of distractors. No outlier RTs were found in Experiment 3. The results were analyzed using 3-way within-subjects ANOVAs. The independent variables corresponded to the type of figure (line-end real contour figure, line-end illusory contour figure), the number of distractors (4 or 8), and the number of enumerated targets (1-9).

**Error Rate**

Error rates were examined using a 2x2x9 within-subjects ANOVA. Overall the error rate was low, $M = 5.50\%$, $SE = 0.50\%$, indicating that participants were using subitizing or counting
and not estimation. As shown in Figure 7a, there was a main effect of type of figure, $F(1, 15) = 6.15, p < .05$, partial $\eta^2 = .29$; more errors were made when enumerating illusory contour figures than real contour figures. There was also the expected main effect of number of targets, $F(4.33, 64.88) = 9.17, p < .01$, partial $\eta^2 = .39$, wherein the number of errors tended to increase as the number of targets increased. No other effects were significant, all $Fs < 2.20$, all $ps > .05$.

The main effect for type of figure, $F(1, 15) = 19.02, p < .01$, partial $\eta^2 = .56$, was surprising as it meant that RT was higher when enumerating illusory contour figures than when enumerating real contour figures (see Figure 7b). There was also the usual main effect of increasing RT with an increasing number of targets, $F(2.33, 34.86) = 280.28, p < .01$, partial $\eta^2 = .95$. As it was expected that both the line end illusory contour figures and the real contour controls would be enumerated using the same strategy, it was surprising to find a significant interaction between the type of figure and the number of targets, $F(3.74, 56.02) = 3.44, p < .05$, partial $\eta^2 = .19$. The enumeration strategy dichotomy hidden in this interaction will be examined further in the enumeration RT slope section, so that the type of enumeration used for each figure can be more accurately assessed.

Predictably, there was a main effect of number of distractors, $F(1, 15) = 40.96, p < .01$, partial $\eta^2 = .73$, indicating that RT increased with an increasing number of distractors. However this effect was qualified by a significant interaction between number of targets and the number of distractors in the display, $F(4.03, 60.49) = 3.03, p < .05$, partial $\eta^2 = .17$, and the significant type of figure and number of distractors interaction, $F(1, 15) = 23.08, p < .01$, partial $\eta^2 = .61$. The three-way interaction was not significant, $F(3.90, 58.47) = .95, p > .05$. The interaction between the number of targets and the number off distractors was not of theoretical interest and was thus
not examined further. The interaction between the type of figure and the number of distractors, however, was very interesting and was examined in the context of the distractor RT slope.

_Distractor RT Slope_

To examine the significant type of figure and number of distractors interaction, the RT slope between four and eight distractors for one target was calculated for each type of figure. The RT slope for distractors (for one target) is analogous to the target-present RT slope in visual search paradigms, because there is one target and a varying number of distractors. This one-way ANOVA revealed that the distractor RT slope (i.e., target-present search slope) for the real contour control figure (-4.17 ms/item) was significantly lower than the distractor RT slope for the line-end illusory contour figure (130.33 ms/item), $F(1, 15) = 12.97, p < .01$, partial $\eta^2 = .68$. The distractor RT slope for the real contour control figure is similar to the target-present search slope found in Experiment 1 and by Li, et al. (2008), which was 13.2 ms/item Conversely, the distractor RT slope for the line-end illusory contour figures indicates that the discrimination of the target from the distractors is more attention demanding that would be expected given the results of the search studies (130.33 ms/item in the present study as compared to 13.0 ms/item in Li et al., 2008). Note that this finding is in opposition to the finding from visual search that line-end illusory contour targets can be discriminated from distractors efficiently.

_Enumeration RT slope_

The RT slope of targets was calculated using a regression analysis with the number of targets as the predictor and RT as the criterion. This was done separately for the 1-3 target range and the 6-8 target range so that the slopes of the two ranges could be compared. These two slopes were calculated for each combination of figure type and number of distractors. The RT slope of targets was analyzed using a 2x2x2 within subjects ANOVA. The variables were the
type of figure (line-end real contour figure, line-end illusory contour figure), number of
distractors (four or eight) and the range for the number of targets (1-3 or 6-8). See Table 3.
There was a significant main effect of number of targets range, $F(1, 15) = 6.82, p < .05$, partial $\eta^2 = .31$, but the effect was attenuated by the significant interaction between the type of figure and
the number of targets range, $F(1, 15) = 6.62, p < .05$, partial $\eta^2 = .31$. As hypothesized, the first
post hoc one-way ANOVA revealed that the RT slope for one and three targets was significantly
lower than the RT slope for six and eight targets for the real contour control figures, $F(1, 15) =
5.39, p < .05$, partial $\eta^2 = .37$. In contrast to the findings of visual search studies, there was no
difference in the RT slope between one and three targets and the RT slope between six and eight
targets for the line-end illusory contour figures, $F(1, 15) = .06, p > .05$. This means that real
contour control figures were subitized, but the line-end illusory contour figures were counted.
Contrary to the hypothesis, but in line with the distractor RT slope (target-present slope)
calculated in this analysis, this result indicates that discriminating a target from distractors
requires attention when the figure is defined by line-endings.

There was also a significant interaction between the number of distractors and the type of
figure, $F(1, 15) = 5.95, p < .05$, partial $\eta^2 = .28$. As this interaction was explored in the primary
RT analysis, it will not be examined again here. No other effects emerged, all $F$s < 4.00, all $ps > .05$.

Discussion Experiments 1-3

The results of previous visual search studies (Gurnsey, et al., 1992; Li, et al., 2008) were
replicated. As expected, the real and illusory contour figures were searched equally as efficiently,
indicating that these figures were discriminated from distractors without the use of attention.
Also in accordance to our expectations, it was found that both the line-end real and illusory
contour figures were subitized in the simple enumeration task, meaning that both types of figures were individuated without attention. Surprisingly, the results of the selective enumeration study did not match the pattern of results for the visual search study. Instead of finding that both the real and illusory contour figures were subitized in the selective enumeration task, as was hypothesized, the illusory contour figures were counted. The distractor RT slope for the illusory contour figures was also much higher than the slope for the real contour figures and the visual search slopes found in our research and previous work. Despite the fact that, logically, these two tasks should be measuring the same processes because both present targets with distractors, the results indicate that this is not the case. This indicates that there may be a fundamental difference between discriminating one target shape from distractors and discriminating more than one (or the expectation of discriminating more than one) target from distractors. A theoretical exploration of this contradictory finding will be explored in the General Discussion.

**Kanizsa Figures**

**Experiment 4 (Visual Search)**

It was important to ensure that when our figures were presented in a visual search task, the results of previous visual search studies would be replicated. Namely, we wanted to ensure that the Kanizsa figures would produce an inefficient search but the Kanizsa real contour control figures would produce an efficient search (Grabowecky & Treisman, 1989; Li, et al., 2008). By replicating these results we could be certain that the results of the enumeration studies could be compared to the results of visual search studies. To replicate the results we used Kanizsa illusory contour rectangles and Kanizsa real contour control rectangles in visual search displays where in which the target (vertical rectangle) was either present or absent with 4, 6, 8 or 12 distractors, as Li, et al. (2008) did.
Method

Design

We manipulated the type of figure (real or illusory), the target presence (present or absent) and the number of targets in the visual search displays. The effect of these variables on error rate, RT and RT slope was measured. The experiment was completed entirely within subjects.

Participants

Sixteen participants (age: 17-26, $M = 18.5$, $SE = 2.1$; males = 4) took part in this study.

Materials

The materials in this Experiment were the same as those in Experiment 1 with the following exceptions. Only Kanizsa class figures were used. The Kanizsa-class figures were composed of four black (2.46 cd/m$^2$, RGB: 0,0,0) “pacmen” inducers at each of the four corners of the induced rectangle. Each pacman had a radius of 0.17° of visual angle. The real contour figures included the inducers for the illusory contour rectangles as well as a 0.05° of visual angle wide black contour around the rectangle (Figure 2). Kanizsa-class figures appeared on a white (78.79 cd/m$^2$, RGB: 256,256,256) background, creating a contrast between the figures and background of 94%. The Kanizsa-class rectangles were presented on an invisible 135 x 105 mm, 9 by 7 grid, which subtended 10.92° x 8.53° of visual angle. The figures appeared in every other position so that the pacmen would never touch, even with the maximum amount of jitter. Therefore, the target and distractor rectangles could appear in columns 1, 3, 5, 7, or 9 and rows 1, 3, 5 or 7 in the invisible 9 by 7 grid. This created a minimal distance between figures of 0.98° of visual angle. The stimuli appeared randomly in these grid positions.

Procedure
The procedure for this Experiment was the same as the procedure for Experiment 1.

**Results**

Before beginning the analysis, the data was screened for outliers. Trials with a RT greater than 2.5 SDs away from that participant’s mean for that figure type, target presence and number of distractors were dropped. This meant that 1.1% of trials were dropped in this analysis. The effect of the type of figure (real or illusory), target presence (present or absent) and number of distractors (4, 6, 8, or 12) on error rate, RT and RT slope was then analyzed.

**Error Rate**

Participants made relatively few errors when searching for Kanizsa class figures, $M = 3.50\%$, $SE = 0.50\%$. More errors were made when searching for illusory contour figures compared to real contour figures, $F(1, 18) = 19.94, p < .05$, partial $\eta^2 = 0.53$, and when there was a target present, $F(1, 18) = 37.30, p < .05$, partial $\eta^2 = 0.68$, see Figure 8a. Although these two effects interacted, $F(1, 18) = 29.26, p < .05$, partial $\eta^2 = 0.62$, as did the type of figure and number of distractor effects, $F(2.32, 41.82) = 3.66, p < .05$, partial $\eta^2 = 0.17$, only the target present illusory contour condition had error rates over 10% (the highest was 13.70%).

**RT**

There were the standard effects of target presence, $F(1, 18) = 62.59, p < .05$, partial $\eta^2 = 0.78$, and number distractors, $F(1, 18) = 60.89, p < .05$, partial $\eta^2 = 0.77$, wherein RT was higher when there was no target in the display and increased as the number of distractors increased, see Figure 8b. In line with our hypothesis, illusory contour figures took longer to find than real contour figures, $F(1, 18) = 136.47, p < .05$, partial $\eta^2 = 0.88$. All the interactions were significant, all $Fs > 5.50$, all $ps < 0.05$, however, because the goal of analyzing the RTs was to determine the efficiency of the searches, these will be addressed in the RT slope analysis.
The typical effect of a higher slope in the target absent trials emerged, $F(1, 18) = 44.98, p < .05$, partial $\eta^2 = 0.71$, see Table 4. In line with our hypothesis, the slope of the illusory contour figures was higher than the slope for the real contour figures, $F(1, 18) = 78.63, p < .05$, partial $\eta^2 = 0.81$, and the interaction between the type of figure and the number of targets was significant, $F(1, 18) = 8.48, p < .05$, partial $\eta^2 = 0.32$. A post hoc analysis revealed that the slope for the real contour figures was much lower than the slope for the illusory contour figures both when the display had no targets, $F(1, 18) = 46.39, p < .05$, partial $\eta^2 = 0.72$, and when the display contained a target, $F(1, 18) = 8.92, p < .05$, partial $\eta^2 = 0.33$. This pattern of results confirms our hypotheses and matches previous literature that the search for real contour figures was much more efficient than the search for illusory contour figures, see Table 4 (Li, et al., 2008). Because these results match the findings of previous visual search studies, a direct comparison can be made between visual search findings and our enumeration results.

**Experiment 5 (Simple Enumeration)**

The purpose of this study was to determine if the individuation of Kanizsa real and illusory contour figures could be accomplished without the use of attention by using a simple enumeration task. If there is a difference between the RT slopes for 1 to 3 items and 6-8 items, then the figures have been subitized and therefore attention was not needed to individuate those figures. If, however, there is no difference between the slopes for small and larger numbers of targets, the figures were counted and attention was needed to individuate the figures.

Visual search experiments have found that Kanizsa real contour control figures are searched efficiently, but that illusory contour figures are searched inefficiently. Logically, if a figure can be formed into a unit and discriminated from distractors efficiently, then the figure
will be individuated without attention. This statement was supported by the results of the line-end class simple enumeration study as well. It is therefore hypothesized that the Kanizsa real contour control rectangles will be subitized. In contrast, the Kanizsa illusory contour figures required attention to be formed into units and discriminated from distractors (produced an inefficient search; Grabowecky & Treisman, 1989; Li et al., 2008). If the Kanizsa illusory contour figures are subitized in the simple enumeration task, it indicates that the individuation of these figures occurs without attention. However, if the Kanizsa illusory contour figures need to be counted in the simple enumeration task, it indicates that these figures do require attention to be individuated.

**Methods**

*Design*

To conduct this experiment, we manipulated the number of targets (1-9) and the type of figure (illusory contour figure or real contour figure) to examine the effects on error rate, RT and enumeration RT slope. The experiment was conducting entirely within subjects.

*Participants*

Results were included from 16 participants (age: $M = 18.50$, $SD = 2.13$; male = 4) with normal or corrected-to normal vision. Three participants were dropped from the analysis (18.75% of the sample, age: $M = 17.67$, $SD = 0.58$; male = 2) due to high error rates in Experiment 5.

*Materials*

The figures in this Experiment appeared in the same 7 x 7 grid as the line-end figures (see Experiment 1), but only in rows 1, 3, 5, or 7 and columns 1, 3, 5, or 7.

*Procedure*
The same procedure was used in this Experiment as the line-end class simple enumeration study (Experiment 2).

**Results**

The goal of this Experiment was to examine the effect of target numerosity (1-9) and type of figure (illusory contour figure or real contour figure) on error rate, RT and RT enumeration slope of Kanizsa class figures in a simple enumeration task. Because the goals of this analysis match those of Experiment 2, the same analyses were used here (2-way ANOVAs). A trial was considered an outlier if it was greater than 2.5 SDs away from that participant’s mean for that type of figure and that number of targets, and as a consequence, 1.6 % of trials were dropped.

**Error Rate**

As expected, given the instructions to enumerate with accuracy, the overall error rate was low, $M = 2.40\%$, $SE = 0.40\%$ and only the usual effect of errors increasing as the number of targets increased emerged, $F(3.48, 52.16) = 8.95$, $p < 0.01$, partial $\eta^2 = 0.37$, see Figure 9a. No other effects were significant, all $Fs < 2.00$, $ps > 0.05$.

**RT**

As is standard for enumeration studies, RT increased as the number of targets increased, $F(2.44, 36.66) = 307.12$, $p < 0.01$, partial $\eta^2 = 0.95$. Neither the main effect of figure type nor the interaction were significant, $Fs < 2.80$, $ps > 0.05$, see Figure 9b.

**Enumeration RT slope**

Only the main effect of the number of targets was significant, $F(1, 15) = 70.91$, $p < 0.01$, partial $\eta^2 = 0.83$, meaning that the slope for 1 to 3 targets was lower than the slope for 6 to 8 targets, or that the figures were subitized, see Table 5. This supports our hypothesis that the real contour control figures would be individuated without attention, as attention was not needed to
enumerate them in the simple enumeration task. This finding also divulged more about the way that Kanizsa illusory contour figures are processed. Kanizsa illusory contour figures were subitized in the simple enumeration task, which means despite these figures needing attention to be discriminated from distractors, they do not need attention to be individuated.

**Experiment 6 (Selective Enumeration)**

The goal of Experiment 6 was to examine the attentional demands of discriminating Kanizsa illusory contour targets from Kanizsa illusory contour distractors with a selective enumeration task. As in Experiment 3, two types of slopes were calculated for each type of figure: the distractor RT slope and the enumeration RT slope. The distractor RT slope is analogous to the target present search slope because it is the calculation of the increase in RT to process one target over an increasing number of distractors (four to eight horizontal rectangles). The enumeration RT slope is the increase in RT over an increasing number of targets. A difference between the enumeration RT slope for a small (1 to 3) number of targets and a larger (6 to 8) number of targets indicates that subitizing has occurred and attention was not needed to discriminate targets from distractors. Alternatively, if there is no difference between the enumeration RT slopes for a small and larger number of targets, then the targets must be counted, indicating that attention was needed to discriminate targets from distractors.

Visual search studies have found that Kanizsa real contour figures were searched efficiently, but the Kanizsa illusory contour figures were searched inefficiently. This means that the real contour targets were distinguished from distractors without attention, but that the illusory contour targets needed attention to be distinguished from distractors. We hypothesize that the results of this selective enumeration experiment will reflect the same pattern. Specifically, we expect that the distractor RT slope for the real contour figures will be low (comparable to target
present search slopes) and that the enumeration RT slopes will show that the figures were subitized. We also expect that the illusory contour distractor RT slope will be high and the enumeration RT slope will indicate that the figures had to be counted.

Methods

Design

In this experiment, the number of targets (1-9), the number of distractors (4 or 8) and the type of figure (real or illusory) were manipulated in order to examine the effects of these manipulations of error rate, RT and RT slope. The study was entirely within subjects.

Participants

Sixteen participants’ data was kept for analysis (age: $M = 18.8$, $SD = .96$; male = 5). Seven participants had to be excluded due to error rates in excess of 30 percent (30.43%, age: $M = 20.29$, $SD = 2.21$; male = 3). The unfortunately high drop rate was due to participants taking “shortcuts” in this experiment as well.

Materials

The materials used in this Experiment were the same as those used in Experiment 3 with the following exceptions. Only Kanizsa-class figures were used in Experiment 6. The figures could appear randomly in the same positions of the 9 x 7 grid that they could in Experiment 4.

Procedure

The procedure for Experiment 6 was identical to that of Experiment 3.

Results

The analysis strategy was the same as that in Experiment 3, as the goal was also to examine the effects of the number of targets, number of distractors and type of figure on error rate, RT, and enumeration RT slope in a selective enumeration task. The data was screened for
RT outliers by dropping any trial that was greater than 2.5 SDs away from a participant’s mean for each combination of the type of target, target numerosity and distractor numerosity. Only 0.6% of trials were dropped as outliers in Experiment 6.

**Error Rate**

Overall the error rate was low, $M = 6.10\%, \ SE = 0.60\%$, indicating that participants were using subitizing or counting and not estimation. The familiar main effect of the number of targets was significant, $F(5.30, 79.55) = 7.25, p < .01$, partial $\eta^2 = .33$; errors increased as the number of targets increased, see Figure 10a. No other effects emerged, all $Fs < 3.7$, all $ps > .05$.

**RT**

Unsurprisingly, there was a significant main effect of the type of figure, $F(1, 15) = 179.64, p < .01$, partial $\eta^2 = .93$, see Figure 10b. Participants were faster to enumerate real contour control figures than Kanizsa illusory contour figures. As is typical of enumeration studies, RT was significantly slower with an increasing number of targets, $F(2.51, 37.68) = 248.63, p < .01$, partial $\eta^2 = .94$, and an increasing number of distractors, $F(1, 15) = 134.16, p < .01$, partial $\eta^2 = .90$. There was also an interaction between the type of figure and number of distractors, $F(1, 15) = 55.49, p < .01$, partial $\eta^2 = .79$, which was examined in the context of the distractor RT slope. No other effects were significant, all $Fs < 2.00$, all $ps > .05$.

**Distractor RT slope**

The post hoc one-way ANOVA revealed that the distractor RT slope (i.e., target-present search slope) for the real contour control figures (111.04 ms/item) was significantly lower than that distractor RT slope for the Kanizsa illusory contour figure (234.47 ms/item), $F(1, 15) = 24.06, p < .01$, partial $\eta^2 = .62$. Although the effect was in the expected direction, it was quite surprising to find that the distractor RT slope was so high for the control figures. A target-present
search slope of over 100 ms/item indicates that the figure requires attention to be discriminated; a finding that goes against visual search literature.

Enumeration RT Slope

Shockingly, the analysis of enumeration RT slope yielded no significant differences between the type of figure or number of targets range, all $F$s < 2.20, all $p$s > .05, see Table 6. This null result meant that the slopes were the same for 1-3 items as they were for 6-8 items and that the slopes for the real contour figures were equal to the slopes of the illusory contour figures. It was hypothesized that the Kanizsa illusory contour figures would be counted, which would be shown by no difference in the RT slope between 1-3 targets and 6-8 targets. This hypothesis is supported by these results, and this portion of the results supports previous literature indicating that Kanizsa illusory contour targets require attention to be discriminated from distractors. In contrast, it is completely unexpected that the real contour controls would be counted as well. This result, in addition to the analysis of the distractor RT slope, indicates that the real contour control targets also needed attention in order to be discriminated from distractors.

Discussion Experiments 4-6

The Kanizsa real contour control and illusory contour figures were subitized in the simple enumeration task. This means that both types of figures can be individuated without attention. Although it was anticipated that the real contour figures would be individuated without attention, the finding that Kanizsa illusory contour figures can be individuated without attention is new. This dichotomy has not been found in previous studies because visual search cannot measure the attentional demands of only individuating figures. This highlights the importance of using multiple paradigms to explore a question.
As has been found in previous visual search studies (Li, et al., 2008), the real contour control figures elicited an efficient search, but the Kanizsa figures elicited an inefficient search. This lead to the hypothesis that Kanizsa real contour figures could be discriminated from distractors without attention, but that the Kanizsa illusory contour targets would need attention to be discriminated from distractors. This hypothesis was only supported for the illusory contour figures. Surprisingly, and in contrast to visual search findings, the real contour control figures were counted in the selective enumeration task, which indicates that the real contour figures needed attention to discriminate them from distractors. An exploration of this odd finding will be presented in the General Discussion.

**General Discussion**

In this series of experiments we found that line-end real and illusory contour figures were both searched efficiently and subitized in the simple enumeration task. However, only the line-end real contour control figures were subitized in the selective enumeration task; the illusory contour figures were counted. In contrast, an inefficient search emerged for the Kanizsa illusory contour figures and an efficient search emerged for the real contour controls. Both types of Kanizsa figures were subitized in the simple enumeration task and counted in the selective enumeration task. The results from the series of experiments for these two classes of figures (line-end and Kanizsa) are quite different. Previous visual search studies (Grabowecky & Treisman, 1989; Gurnsey, et al., 1992; Li, et al., 2008) have found this difference in the attentional demands of processing Kanizsa and line-end class figures as well. Gurnsey, et al. (1992) found that search for a line-end illusory contour figure was efficient and Li, et al. (2008) found that a search for line-end illusory contour targets was equally as efficient as search for a real contour figure. Conversely, search for a Kanizsa illusory contour figure was found to be
inefficient (Grabowecky & Treisman, 1989; Li, et al., 2008). This clearly indicates that there is a difference in the attentional demands of processing these two classes of figures (see Figure 11 for a summary of the findings).

There were also differences in the pattern of results between the visual search studies and the selective enumeration studies. Namely, for the line-end illusory contour figures and for the Kanizsa real contour control figures, search was efficient, but the distractor RT slope calculated from the results of the selective enumeration study (equivalent to the target-present RT slope) indicated an inefficient search and the figures were also counted in the selective enumeration task. This was true even though both present targets with distractors and should therefore be measuring the attentional demands of discriminating targets from distractors. Additionally, previous research has shown that figures that are searched efficiently also tend to be subitized in a selective enumeration task (Trick & Enns, 1997b). Clearly, however, there is some difference in the way these two tasks are completed. This is likely due to a difference in the way a task with only one (or none) target(s) is processed by the visual system and the way a task with multiple targets is processed. This difference can be explained using FINST (FINgers of INSTantiation) theory (Trick & Pylyshyn, 1993; 1994).

FINST theory suggests that there are a limited number (four on average) of spatial indexes that can be attached in parallel to things in our visual field. FINSTs are attached to feature clusters that have been formed in the preattentive (spatially parallel) stage of vision. The FINST sticks to this feature cluster and acts as a channel through which attention can be allocated to the feature cluster. A FINST will remain attached to something until another object “grabs” it or a decision is made to move them to other thing (Pylyshyn, 2007; Trick & Pylyshyn, 1993; 1994). Because FINSTs attach to feature clusters that are amalgamated in the early stages
of vision, before one area at a time processing is required, if an object is not perceived as a whole before FINSTs are attached, the object cannot be processed as a complete object without attention. However, because there are around four indexes, it may be possible to process a single rectangle without attention. This is because if a contour or side of the figure can be clustered into a thing in preattentive vision, a FINST can attach to each and the relative sizes of the sides can be compared. Attention is thus not needed to process the figure or reallocate the FINSTs. If however, there is more than one object, when the FINSTs have finished processing the first object, attention must be used to transfer the FINSTs from one object to the next in a serial search, resulting in an attention-demanding task.

Another surprising finding was that the selective enumeration of Kanizsa real contour control figures was attention-demanding. This is particularly odd because connectivity is a Gestalt feature that is considered to be one of the building blocks of feature clustering that occurs in the preattentive stage of vision (Kanizsa, 1976). This may be because the figures themselves are more complicated than those typically used in orientation-based tasks. Most orientation-discrimination search or enumeration tasks use very simple rectangles or lines (e.g., Cavanagh, Arguin & Treisman, 1990; Trick & Enns, 1997b; Wolfe, Cave & Franzel, 1989), whereas our Kanizsa real contour control figures were composed of a rectangle plus pacmen corners. The increased complication of the figures (orientation information plus curvature information at the corners) may make it necessary to use attention to discriminate targets from distractors in an orientation-based enumeration task. One way to explore this possibility would be to compare results between the real contour control figures (with pacmen corners) with regular rectangles (no pacmen corners) and regular rectangles with the pacmen are present, but detached from the contours of the real rectangle. The results of this comparison would reveal if having the pacmen
attached to the rectangles or simply being in the scene make the task more attentionally
demanding than a an orientation-discrimination task with standard stimuli.

Future research should also examine the nature of the differences in attentional demands
elicited by line-end and Kanizsa illusory contours. A possible reason for this difference could be
the nature of each type of inducer. Pacmen have a broad real contour that matches up with
another broad real contour to induce an illusory contour, whereas line-end inducers are a series
of very small but more spread out real contours that are aligned in such a way as to induce an
illusory contour. If the inducers were more similar for the two classes of illusory contours, the
attentional demands of the two classes of contours might be similar. For example, if line-end
inducers were much broader, but there were fewer lines, they would appear more like Kanizsa
inducers (or vice versa) and the resulting attentional demands of the two types of illusory
contours would become more similar.

More research is needed to determine the reasons for our unexpected findings, however,
there are a few conclusions we can draw from the results of this series of experiments. Attention
is not needed to individuate illusory contour figures or real contour figures of the line-end class
or the Kanizsa class. Line-end real contour and illusory contour targets can be discriminated
from distractors if there is only one target (or the possibility of one target). If more targets are
present, the attentional demands of discriminating real contour targets from distractors does not
change, but attentional demands increase when the targets and distractors are illusory contour
figures. In contrast, attention is always needed in order to discriminate Kanizsa illusory contour
targets from distractors. Discriminating Kanizsa real contour targets from distractors is
attentionally demanding only when the task involves more than one target (but not when there is
only the possibility of one or no target).
References


Table 1.

*Search reaction time (RT) slopes, M (SE), in ms/item for the line-end class figures from Experiment 1 and from Li, et al. (2008)*

<table>
<thead>
<tr>
<th></th>
<th>Experiment 1</th>
<th>Li, Cave and Wolfe (2008)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Real contour figure</td>
<td>Illusory contour figure</td>
</tr>
<tr>
<td>Target present</td>
<td>1.38 (2.59)</td>
<td>-0.72 (1.81)</td>
</tr>
<tr>
<td>Target absent</td>
<td>14.70 (3.21)</td>
<td>15.78 (3.83)</td>
</tr>
</tbody>
</table>

Table 2.

*Enumeration reaction time (RT) slopes in ms/item, M (SE), for 1-3 and 6-8 target ranges in the simple enumeration task (Experiment 2).*

<table>
<thead>
<tr>
<th></th>
<th>Line-end real contour figure</th>
<th>Line-end illusory contour figure</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-3 Target Range</td>
<td>75.35 (12.30)</td>
<td>65.52 (11.34)</td>
</tr>
<tr>
<td>6-8 Target Range</td>
<td>322.72 (46.96)</td>
<td>266.30 (45.15)</td>
</tr>
</tbody>
</table>
Table 3.

Enumeration reaction time (RT) slopes in ms/item, M (SE), for 1-3 and 6-8 target ranges in the selective enumeration task using line-end class stimuli (Experiment 3).

<table>
<thead>
<tr>
<th>Number of Distractors</th>
<th>Line-end real contour figure</th>
<th>Line-end illusory contour figure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Four</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1-3 Target Range</td>
<td>117.69 (46.97)</td>
<td>302.67 (42.03)</td>
</tr>
<tr>
<td>6-8 Target Range</td>
<td>385.51 (73.46)</td>
<td>309.82 (34.68)</td>
</tr>
<tr>
<td>Eight</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1-3 Target Range</td>
<td>202.10 (52.05)</td>
<td>225.14 (53.05)</td>
</tr>
<tr>
<td>6-8 Target Range</td>
<td>321.87 (37.37)</td>
<td>163.88 (43.96)</td>
</tr>
</tbody>
</table>

Table 4.

Search reaction time (RT) slopes, M (SE), in ms/item for the Kanizsa class figures from Experiment 4 and from Li, et al. (2008)

<table>
<thead>
<tr>
<th></th>
<th>Experiment 4</th>
<th>Li, Cave and Wolfe (2008)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Real contour figure</td>
<td>Illusory contour figure</td>
</tr>
<tr>
<td>Target present</td>
<td>9.54 (1.99)</td>
<td>25.24 (4.85)</td>
</tr>
<tr>
<td>Target absent</td>
<td>25.55 (4.75)</td>
<td>77.12 (8.43)</td>
</tr>
</tbody>
</table>
Table 5.

*Enumeration reaction time (RT) slopes in ms/item, M (SE), for 1-3 and 6-8 target ranges in the simple enumeration task (Experiment 5).*

<table>
<thead>
<tr>
<th>Target Range</th>
<th>Kanizsa real contour figure</th>
<th>Kanizsa illusory contour figure</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-3</td>
<td>63.83 (11.40)</td>
<td>77.74 (10.50)</td>
</tr>
<tr>
<td>6-8</td>
<td>328.35 (43.53)</td>
<td>334.05 (35.46)</td>
</tr>
</tbody>
</table>

Table 6.

*Enumeration reaction time (RT) slopes in ms/item, M (SE), for 1-3 and 6-8 target ranges in the selective enumeration task using Kanizsa class stimuli (Experiment 6).*

<table>
<thead>
<tr>
<th>Number of Distractors</th>
<th>Kanizsa real contour figure</th>
<th>Kanizsa illusory contour figure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Four</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1-3 Target Range</td>
<td>339.12 (39.63)</td>
<td>379.52 (33.74)</td>
</tr>
<tr>
<td>6-8 Target Range</td>
<td>275.48 (52.05)</td>
<td>382.90 (54.55)</td>
</tr>
<tr>
<td>Eight</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1-3 Target Range</td>
<td>408.23 (44.02)</td>
<td>361.43 (58.95)</td>
</tr>
<tr>
<td>6-8 Target Range</td>
<td>361.01 (69.63)</td>
<td>353.67 (65.55)</td>
</tr>
</tbody>
</table>
Figure 1. Illusory contour figures. (a) Kanizsa illusory contour rectangle on the left. (b) Line-end illusory contour rectangle on the right.

Figure 2. Real contour figures. (a) Kanizsa real contour rectangle on the left. (b) Line-end real contour rectangle on the right.
Figure 3. An example of a simple enumeration task for line-end illusory contour figures. In this figure, there are two targets.

Figure 4. An example of a selective enumeration task for line-end illusory contour figures. In this figure, there are two targets (vertical rectangles) and four distractors (horizontal rectangles).
Figure 5a. Mean error rates in percentages for both types of line-end class figures for target present and target absent trials in the visual search task (Experiment 1). Standard error bars represent standard errors.

Figure 5b. Mean reaction time (RT) in ms for both types of line-end class figures for target present and target absent trials in the visual search task (Experiment 1). Standard error bars represent standard errors.
Figure 6a. Mean error rates in percentages for each type of line-end class figure for each number of targets in the simple enumeration task (Experiment 2). Standard error bars represent standard errors.

Figure 6b. Mean reaction time (RT) in ms for each type of line-end class figure for each number of targets in the simple enumeration task (Experiment 2). Standard error bars represent standard errors.
Figure 7a. Mean error rates in percentages for line-end class figures for each number of targets and distractors in the selective enumeration task (Experiment 3). Standard error bars represent standard errors.

Figure 7b. Mean reaction time (RT) in ms for line-end class figures for each number of targets and distractors in the selective enumeration task (Experiment 3). Standard error bars represent standard errors.
Figure 8a. Mean error rates in percentages for both types of Kanizsa class figures for target present and target absent trials in the visual search task (Experiment 4). Standard error bars represent standard errors.

Figure 8b. Mean reaction time (RT) in ms for each type of Kanizsa-class figure for target present and target absent trials in the visual search task (Experiment 4). Standard error bars represent standard errors.
**Figure 9a.** Mean error rates in percentages for each type of Kanizsa-class figure for each number of targets in the simple enumeration task (Experiment 5). Standard error bars represent standard errors.

**Figure 9b.** Mean reaction time (RT) in ms for each type of Kanizsa-class figure for each number of targets in the simple enumeration task (Experiment 5). Standard error bars represent standard errors.
**Figure 10a.** Mean error rates in percentages for Kanizsa class figures for each number of targets in the selective enumeration task (Experiment 6). Standard error bars represent standard errors.

**Figure 10b.** Mean reaction time (RT) in ms for Kanizsa class figures for each number of targets in the selective enumeration task (Experiment 6). Standard error bars represent standard errors.
**Figure 11.** A summary of the findings from the three different paradigms and the processes associated with each, for each type of figure.