# Effects of aging on figure-ground perception: Convexity context effects and competition resolution

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**We examined age-related differences in figure-ground perception by exploring the effect of age on Convexity Context Effects (CCE; Peterson & Salvagio, 2008). Experiment 1, using Peterson and Salvagio's procedure and black and white stimuli consisting of 2 to 8 alternating concave and convex regions, established that older adults exhibited reduced CCEs compared to younger adults. Experiments 2 and 3 demonstrated that this age difference was found at various stimulus durations and sizes. Experiment 4 compared CCEs obtained with achromatic stimuli, in which the alternating convex and concave regions were each all black or all white, and chromatic stimuli in which the concave regions were homogeneous in color but the convex regions varied in color. We found that the difference between CCEs measured with achromatic and colored stimuli was larger in older than in younger adults. Our results are consistent with the hypothesis that the senescent visual system is less able to resolve the competition among various perceptual interpretations of the figure-ground relations among stimulus regions.**

## Introduction

Figure-ground (FG) perception is one possible outcome of perceptual organization processes operating on a border between two regions in the visual input. FG processes enable us to assign contours to objects, which are perceived as figures lying in front of a background, and is a critical component of perception in naturalistic contexts. Given the importance of the phenomenon, it has been studied for nearly a century; yet, many questions remain about the mechanisms underlying FG organization.

The convexity of a border between adjacent regions is one of the classic configural cues involved in FG perception first discussed by Rubin (1958). Specifically, the region on the convex (VEX) side of a border (i.e., the *VEX region*) is more likely than the region on the concave (CAV) side of the border (i.e., the *CAV region*) to be perceived as a shaped entity, or figure, lying in front of a shapeless background (Kanizsa & Gerbino, 1976). Some authors, including Rubin (1958), have held convexity to be a weak cue while others, including Kanizsa and Gerbino (1976), have argued that it is a relatively strong cue. The reality appears to be that the probability of perceiving VEX regions as figures actually depends on the context of the border of interest.

Peterson and Salvagio (2008) developed a novel method to examine the influence of convexity on FG perception and how this influence is affected by the context of surrounding regions. Their stimuli, illustrated in Figure 1, contained 2, 4, 6, or 8 alternating black and white regions with VEX/CAV borders. A red probe was located on one of the regions adjacent to the central border and occurred equally on each side, region type (VEX vs. CAV), and polarity (black vs. white). Participants viewed each stimulus for 100 ms, and indicated whether the probe was on or off the region they perceived as figure. Peterson and Salvagio found that when the stimulus contained only two regions separated by a VEX/CAV border (left panel, Figure 1), participants indicated that they perceived the VEX region as figure on 57% of the trials. In other words, VEX regions were perceived as figure significantly more than CAV regions, confirming that

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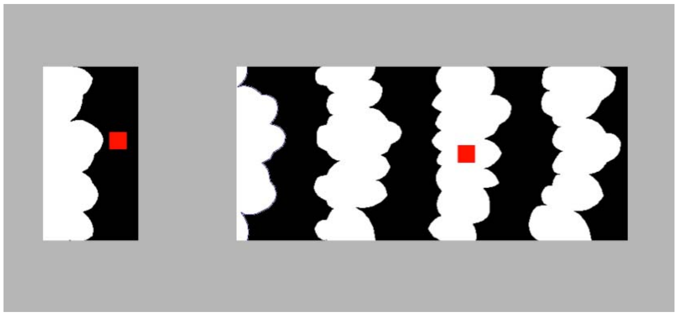

Figure 1. Convexity stimuli used by Peterson and Salvagio (2008). This figure contains 2- and 8-region black and white (BW) stimuli, composed of alternating VEX and CAV regions. The red probe is on the black CAV region in the 2-region stimulus, and on a white VEX region in the 8-region example. The side, color, and region type that the probe was placed on was balanced across the stimulus set. The background surrounding the stimuli was a medium gray measuring 53.5 cd/m$^2$, black regions were 0.6 cd/m$^2$, and white regions were 96.4 cd/m$^2$.

convexity is a figural cue, but its influence was not strong; even young subjects don't always perceive the VEX regions as figures in 2-region displays. Interestingly, the probability that participants perceived the central VEX region as the figure increased as the number of regions surrounding the central border increased from 2 to 8. Hence, the context surrounding the region of interest affected the proportion of trials where the VEX region was perceived as figure, such that in 8-region displays (right panel, Figure 1) observers perceived the VEX region as the figure on nearly 90% of the trials. This context effect was later replicated with the configural cue of symmetry (Mojica & Peterson, 2014).

This so-called convexity context effect (CCE) persists when the VEX regions are heterogeneous (HET) in color, but is abolished when the CAV regions vary in color (Peterson & Salvagio, 2008). This indicates that homogeneity across potential background segments is required for the increase in P(VEX=Figure) observed with increased region number, so long as there are VEX regions that signal foreground. This suggests that heterogeneity across spatially separated CAV regions is inconsistent with the interpretation of those regions being parts of unified background. The CCE also is abolished when a mask is presented 0–50 ms after the stimulus offset, and re-emerges with increased stimulus-mask asynchrony (Salvagio & Peterson, 2010). Peterson and Salvagio (2008) interpreted their results as showing that FG perception results from inhibitory competition between alternative perceptual interpretations of the display, which takes time and is mediated by context, including the number of regions and the homogeneity of color across regions. This inhibitory-competition model of FG perception has been supported by behavioral findings indicating suppression of object representations falling on the perceived grounds (Peterson & Skow, 2008), functional imaging results demonstrating suppression of voxels representing spatial locations of ground-side image regions (Cacciamani, Scalf, & Peterson, 2015; Likova & Tyler, 2008), and electrophysiological evidence consistent with processing mechanisms involving online inhibitory suppression in response to differing degrees of FG competition (Sanguinetti, Trujillo, Schnyer, Allen, & Peterson, 2016).

The suggestion that FG perception is based on inhibitory competition raises the possibility that FG perception may change during healthy aging. Evidence from anatomical, physiological, and psychophysical studies suggests that aging may affect the balance of excitatory and inhibitory mechanisms in visual cortex. For example, a study of human visual cortex from older adults found that there were changes in several pre- and postsynaptic GABAergic markers (Pinto, Hornby, Jones, & Murphy, 2010), consistent with an aging-related reduction in the efficacy of the GABAergic system. A reduction in the efficacy of inhibitory mechanisms is thought to contribute to the age-related decline in orientation and directional selectivity of V1 neurons (Leventhal, Wang, Pu, Zhou, & Ma, 2003; Schmolesky, Wang, Pu, & Leventhal, 2000), and perhaps the reduction in selectivity of speed and directional MT neurons (Liang et al., 2010; Yang et al., 2009) in older monkeys. A decrease in the density of GABA-immunoreactive neurons also has been associated with neurophysiological changes in visual neurons in cat striate cortex (Hua, Kao, Sun, Li, & Zhou, 2008) consistent with an age-related decline in inhibitory function. The results of several psychophysical studies are consistent with the hypothesis that inhibitory cortical neural circuits are diminished by aging. For example, motion detection and discrimination thresholds are consistent with models of aging that incorporate broader directional tuning and increased internal noise (Bennett, Sekuler, & Sekuler, 2007), similar to the changes found in neurophysiological studies. Age-related changes in the ability to recognize faces across different viewpoints (Habak, Wilkinson, & Wilson, 2008) also are consistent with neural models that incorporate a reduction of inhibition with aging (Wilson, Mei, Habak, & Wilkinson, 2011). Age-related changes in inhibitory mechanisms, based on a model proposed by Lehky and Blake (1991), also may play a role in older observers' increased suppression in binocular rivalry tasks (Beers, Bennett, & Sekuler, 2013; Norman, Norman, Pattison, Taylor, & Goforth, 2007). As well, spatial suppression in a motion discrimination task is significantly lower in older adults compared to younger adults (Betts, Sekuler, & Bennett, 2009, Betts, Taylor, Sekuler, & Bennett, 2005), a result consistent with the idea that aging alters the balance between excitatory and inhibitory mechanisms that encode motion direction (Betts et al. 2012; but also see Govenlock, Taylor, Sekuler, & Bennett, 2009, 2010; Karas & McKendrick, 2012, 2015; Rosen, Sekuler, & Bennett, 2013, for examples of tasks in which aging does not appear to be linked to decreased inhibition).

Hence, a variety of studies suggest that healthy aging may be associated with a change in the balance between excitation and inhibition, with decreased efficacy of inhibitory mechanisms. If inhibitory competition is important for FG perception, one might expect to find both reduced likelihood of seeing convex regions as figures overall (because FG requires competition resolution) and reduced CCEs. The current experiments tested that prediction.

# Experiment 1

Experiment 1 used the method described by Peterson and Salvagio (2008) to measure the CCE in younger and older adults using 2- and 8-region displays.

## Methods

### *Participants*

Two groups of observers participated in this study: The younger group consisted of 25 participants ($M = 22.6$ years, $SD = 4.1$ years) and the older group consisted of 24 participants ($M = 70.0$ years, $SD = 5.9$ years). All of the older participants were compensated $10 per hour for participating, whereas younger participants received partial course credit.

In all experiments, older participants were community-dwelling residents recruited through the McMaster Vision and Cognitive Neuroscience Lab's pool of healthy older adults. All participants underwent a battery of visual and cognitive tests before completing the experiment, including near and far visual acuity (Bailey & Lovie, 1976), and contrast sensitivity (Pelli & Robson, 1988). Participants also completed the Montreal Cognitive Assessment (MoCA; Nasreddine, Charbonneau, & Cummings, 2005), the Mini Mental State Exam (MMSE; Folstein, Folstein, & McHugh, 1975), the Morningness/Eveningness questionnaire (Horne & Ostberg, 1976), and a general health questionnaire. We also measured individual characteristics including handedness, race, years of education, and first language. No participants were excluded through screening.

Every observer participated in two experimental conditions, and the order of the conditions was counter-balanced. The study took approximately 30 minutes to complete.

### *Stimuli and apparatus*

Stimuli were presented on an NEC MultiSync FE992 CRT with a resolution of 1280 × 1024 pixels and a frame rate of 85 Hz. The experiment was controlled with an Apple Power Mac G5 computer using MATLAB (version 7.4.0.287) and the Video and Psychophysics toolboxes (Brainard, 1997; Pelli, 1997).

This study used the 2- and 8-region convexity stimuli from Peterson and Salvagio (2008). Each stimulus consisted of 2 or 8 alternating black and white sections. Adjacent regions composing the stimulus were separated by complex curved borders, and the stimulus boundaries formed straight edges against the background (Figure 1). Black and white regions were always equal in area. The left and right sides of each black/white section were bounded by VEX or CAV borders, making for *regions* that were either VEX or CAV. For example, the 8-region stimulus in Figure 1 is composed of alternating white VEX regions and black CAV regions. The tops and bottoms of each stimulus were separated from the background by horizontal edges, and the left and rightmost regions of each display met the background at vertical edges (see Mojica & Peterson, 2014, for evidence that the shape of display edges matters). The stimulus set was balanced such that the leftmost (and rightmost) region in each pattern was black 50% of the time and VEX 50% of the time. Each stimulus also had a red square probe that was always on one of the two regions adjacent to the pattern's central border. The probe's placement was balanced across trials such that it was on VEX and CAV regions equally often, located to the left and right of the central border equally often and placed on black and white regions equally often. Each curved edge in every stimulus was created by creating 3–15 points that corresponded to minima of curvature. These points were distributed randomly along a virtual vertical contour with slight horizontal jitter, and then smooth curves were drawn upwards and downwards from each point until adjacent arcs intersected to form a curved bump. There were a total of 64 stimuli in each of the 2- and 8-region conditions.

Each stimulus was presented in the center of a uniform display that subtended 22.9° (width) × 17.2° (height) from the viewing distance of 90 cm. The stimuli were 5.4° in height; the mean widths of the 2- and 8-region displays were 2.5° and 11.5°, respectively. The luminance was 53.5 cd/m$^2$ for the background, 0.6 cd/m$^2$ for the black regions, and 96.4 cd/m$^2$ for the white regions. Viewing was binocular, and a head/chin rest was used to stabilize viewing position. The experiment

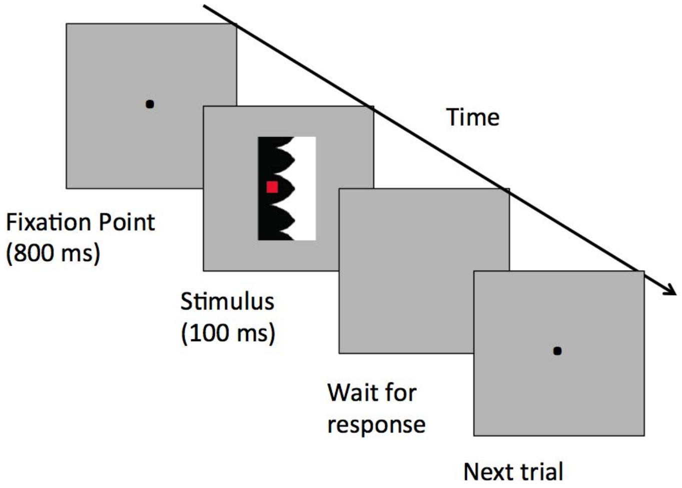

Figure 2. A schematic of the progression of a single trial. Each trial began with a flickering fixation point, and after 800 ms the stimulus was displayed for 100 ms (for Experiment 1, although the stimulus duration was manipulated in later experiments). After stimulus offset, the screen was left with a background gray fill until the participant responded by indicating whether the red probe was ON or OFF the region perceived to be the figure.

took place in a dark and quiet room with the experimental monitor serving as the only light source.

### *Procedure and task*

Every participant completed two blocks of 64 trials: one with 2-region stimuli, and another with 8-region stimuli. Block order was randomly determined, and stimulus presentation order was randomized within each block. No stimuli were repeated. Each block began with five practice trials.

The task was to indicate whether a red probe square appearing on one of the two central regions was ON or OFF the region perceived as figure. Before the experiment began, the experimenter introduced the participant to the concept of FG perception, explaining that figures appear to have a definite shape and appear closer than the adjacent region(s) that are seen as shapeless background. The experimenter stayed in the room while instructions were presented on the screen and participants completed five practice trials of the first condition. After the first block of trials was completed, there was a short break before instructions for the second block were presented on-screen. There were five practice trials, and participants completed the second block.

Each trial began with a central fixation point that flickered against the medium gray background for 800 ms, followed directly by the presentation of an FG stimulus for 100 ms (see Figure 2). The entire screen was filled with background gray 100 ms after the stimulus onset. After stimulus offset, participants indicated which of the two central regions they perceived to be the figure by pressing the ON or OFF button to signal whether the red probe was on or off the perceived *figure*. They were told that there were no wrong answers, and that they should answer based on their first impression while maintaining accuracy. The next trial began immediately after participants made their response.

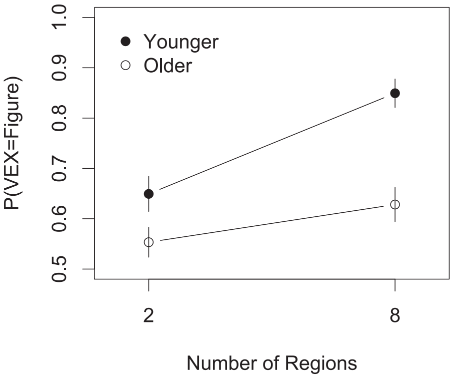

Figure 3. Behavioral performance in Experiment 1. The figure shows the mean proportion of trials on which the convex region was perceived as figure for younger (filled circles) and older (open circles) observers in the 2- and 8-region displays. Error bars represent ±1 *SEM*. In 2-region displays, VEX regions were reported as figure more often than chance for both younger, $t(24) = 4.29$, $p < 0.0001$, and older adults, $t(23) = 1.80$, $p = 0.021$ (one-tailed).

## Results

All statistical analyses were performed using the R statistical computing environment (R Core Team, 2016).

Figure 3 depicts the proportion of stimuli for which the VEX region was perceived as the figure for each condition and each age group. As expected from previous work demonstrating the influence of convexity on FG perception, both age groups indicated the VEX region as figure significantly more than 50% of the time; however, P(VEX=Figure) was higher in younger adults, particularly in the 8-region condition. The CCE is defined as the change in the proportion of VEX responses as the number of regions increases, and therefore the results shown in Figure 3 suggest that the CCE was stronger in younger observers. Here we calculated the CCE as follows:

$$\mathrm{CCE} = P(\mathrm{VEX} = \mathrm{figure})_{\text{8-Region}} - P(\mathrm{VEX} = \mathrm{figure})_{\text{2-Region}} \quad (1)$$

To quantify these effects, data in Figure 3 were analyzed with a 2 (age group) × 2 (region number) × 2

| | *df* | *SS* | *MS* | *F* | Pr(>*F*) |
|---|---|---|---|---|---|
| Age group | 1 | 0.58 | 0.58 | 18.19 | 0.001 |
| Regions | 1 | 0.37 | 0.37 | 25.23 | <0.001 |
| Order | 1 | 0.20 | 0.20 | 6.34 | 0.015 |
| Age group × regions | 1 | 0.11 | 0.11 | 7.53 | 0.009 |
| Age group × order | 1 | 0.002 | 0.002 | 0.05 | 0.83 |
| Regions × order | 1 | 0.02 | 0.02 | 1.39 | 0.24 |
| Age group × regions × order | 1 | 0.003 | 0.003 | 0.19 | 0.66 |
| Residuals (within/mixed) | 44 | 0.64 | 0.014 | | |
| Residuals (between) | 44 | 1.41 | 0.032 | | |

Table 1. Analysis of variance results for Experiment 1.

(condition order) split plot Analysis of Variance (ANOVA). Previous studies examining CCEs used a between observers design, and therefore we included condition order in our analysis to determine if the probability of perceiving the VEX region as figure differed between groups who saw the 2- or 8-region stimuli first. The results of the ANOVA are presented in Table 1. The main effects of Age Group, Region Number, and Order were significant. Importantly, the Age Group × Region Number interaction was significant, indicating that the CCE differed between age groups, and the interaction did not depend on the order of the conditions. The interaction shows that the extent of the CCE was greater for younger observers than older observers, and follow-up analyses indicated that effect of region number was significant in both younger, $t(24) = 4.62$, $p = 0.0012$, Cohen's $d = 1.26$, and older groups, $t(23) = 2.14$, $p = .043$, Cohen's $d = 0.48$. With respect to the main effect of order, observers tended to report VEX region as figure more often when the 8-region condition was conducted first ($M = 0.72$) compared to when the 2-region condition was first ($M = 0.62$).

## Discussion

The current experiment had two main results. First, we replicated the CCE in young adults that was observed by Peterson and Salvagio (2008). Second, our key finding is the interaction between region number and age group. This interaction indicates that, although region number affected the probability of perceiving VEX regions as figure in both age groups, the CCE was significantly lower in older adults compared to younger adults (Figure 3).

Peterson and colleagues (Peterson & Salvagio, 2008; Salvagio & Peterson, 2012) have suggested that the CCE is a manifestation of an inhibitory competition between regions on opposite sides of a border that leads to one region being perceived as a figure and the other as the background. Within this framework, our results suggest that the competitive FG process is less effective in older adults, perhaps due to age-related differences in inhibitory processing. However, other potential causes need to be considered. One possibility is that FG processing is simply slower in older adults. This idea is examined in Experiments 2 and 3. Alternatively, older adults may be less able to spatially integrate information across the large, 8-region stimuli used in the current task. If this is correct, then older adults should also be less sensitive to the effects of region homogeneity reported by Peterson and Salvagio (2008). This hypothesis is examined in Experiment 4.

# Experiment 2

Some age-related differences in perception and cognition may reflect a generalized slowing of perceptual and cognitive processing rather than a qualitative change in processing (Salthouse, 1996). Hence, it is plausible to suggest that the age differences in CCEs found in Experiment 1 were simply the result of slower FG processing in older adults. Might younger observers show reduced CCEs, similar to those observed in older participants, if stimuli were presented for shorter durations? Experiment 2 addressed this question by measuring CCEs in younger observers using shorter stimulus durations.

## Methods

### Participants

Twenty-four younger observers participated in this experiment ($M = 21.5$, $SD = 2.9$ years). Nine of the participants received partial course credit for completing the experiment, whereas the other 15 were compensated $10 per hour after completing the study.

### Procedure

The same methods were used as in Experiment 1, except that two shorter durations (50 ms and 25 ms) were included along with the original stimulus duration of 100 ms. Two- and 8-region stimuli were each shown at three stimulus durations (25, 50, and 100 ms), yielding a total of six experimental conditions. Each condition included 64 trials; stimuli were not repeated within conditions but were repeated across conditions. The presentation orders for region number and stimulus duration were counterbalanced across participants using a Latin square with four subjects per order.

Stimuli were the same as those used in Experiment 1: From the viewing distance of 96 cm, they subtended

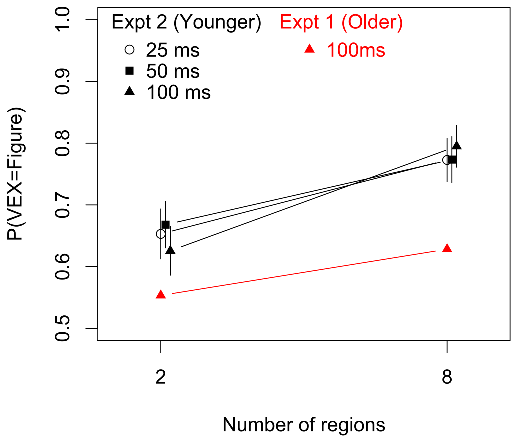

Figure 4. Performance for younger observers with reduced stimulus durations. *M* ±1 *SEM* proportion of figures where VEX region was seen as figure –P(VEX=Figure)—for younger observers in 2- and 8-region displays across the different stimulus duration conditions. The data points for the older group are included in red to allow for direct comparison of CCEs across groups even under such time-constrained conditions. This figure also allows for comparison of the slopes between age groups and demonstrates that even compared to the shallowest CCE slope from Experiment 2, the older group has a reduced effect of region number.

5.1° in height and had a mean width of 2.3° for 2-region and 10.8° for 8-region stimuli. All stimuli were presented in each stimulus duration condition.

### Results

The results are displayed in Figure 4, which shows that there was no obvious effect of stimulus duration on the magnitude of CCEs in younger observers. These observations were supported by a two-way (stimulus duration × region number) within-subjects ANOVA: The main effect of region number was significant, $F(1, 23) = 22.27$, $p < 0.0001$, *partial* $\omega^2 = 0.47$, but the main effect of stimulus duration, $F(2, 46) = 0.12$, $p = 0.89$, and the stimulus duration × region number interaction, $F(2, 46) = 2.00$, $p = 0.15$ were not.

### Discussion

The results of this experiment demonstrated that reducing stimulus duration from 100 ms to 25 ms did not significantly alter the CCE measured in younger observers. Overall, the pattern of results is inconsistent with the hypothesis that reducing stimulus presentation durations by a factor of 2 and 4 in younger observers would shift CCEs towards those observed in older observers. Hence, the results of the current experiment suggest that the age difference observed in Experiment 1 was not caused by simple differences in ability to organize briefly exposed stimuli. To further investigate this issue, Experiment 3 examined whether increasing stimulus duration would increase CCEs in older observers. Experiment 3 also examined whether the magnitude of the CCE in seniors is constrained by their difficulty in quickly processing large stimuli.

## Experiment 3

Our interpretation of the effects of decreasing stimulus presentation time for younger observers may be limited by the fact that, due to age-related differences in visual masking (Kline & Birren, 1975; Farber, Sekuler, & Bennett, 2010), we did not include a mask following stimulus presentation. Thus, it is possible that although younger people viewed short-duration stimuli, visual processing may have continued for longer periods of time after stimulus offset. To more directly assess the effect of processing time on age-related differences in the CCE, it is important also to examine performance under conditions of increased stimulus duration. To that end, the current experiment presented stimuli at both our original presentation duration (100 ms) as well as at a longer duration (250 ms). We did not extend presentation durations beyond that to avoid introducing complications from age-related differences in eye-movements (Munoz, Broughton, Goldring, & Armstrong, 1998; Peltsch, Hemraj, Garcia, & Munoz, 2011; Sharpe & Zackon, 1987). If seniors' CCE was constrained by the relatively short duration in Experiment 1, we would expect that increasing stimulus duration from 100 to 250 ms would increase the CCE obtained in older observers.

Because older observers are known to have different spatial integration limits and reduced effective useful fields of view compared to younger observers (Andersen & Ni, 2008; Del Viva & Agostini, 2007; Richards, Bennett, & Sekuler, 2006; Sekuler, Bennett, & Mamelak, 2000), Experiment 3 also manipulated the spatial scale of the stimuli.

### Methods

#### *Participants*

For Experiment 3, the sample consisted of eight older ($M = 71.5$ years, $SD = 6.5$ years) and eight younger ($M = 23.0$ years, $SD = 2.7$ years) participants. All of the participants were paid $10 for participating, except for two observers from the younger group who were naive volunteers working on other projects in McMaster's Vision and Cognitive Neuroscience lab. The experiment took 30 min to complete.

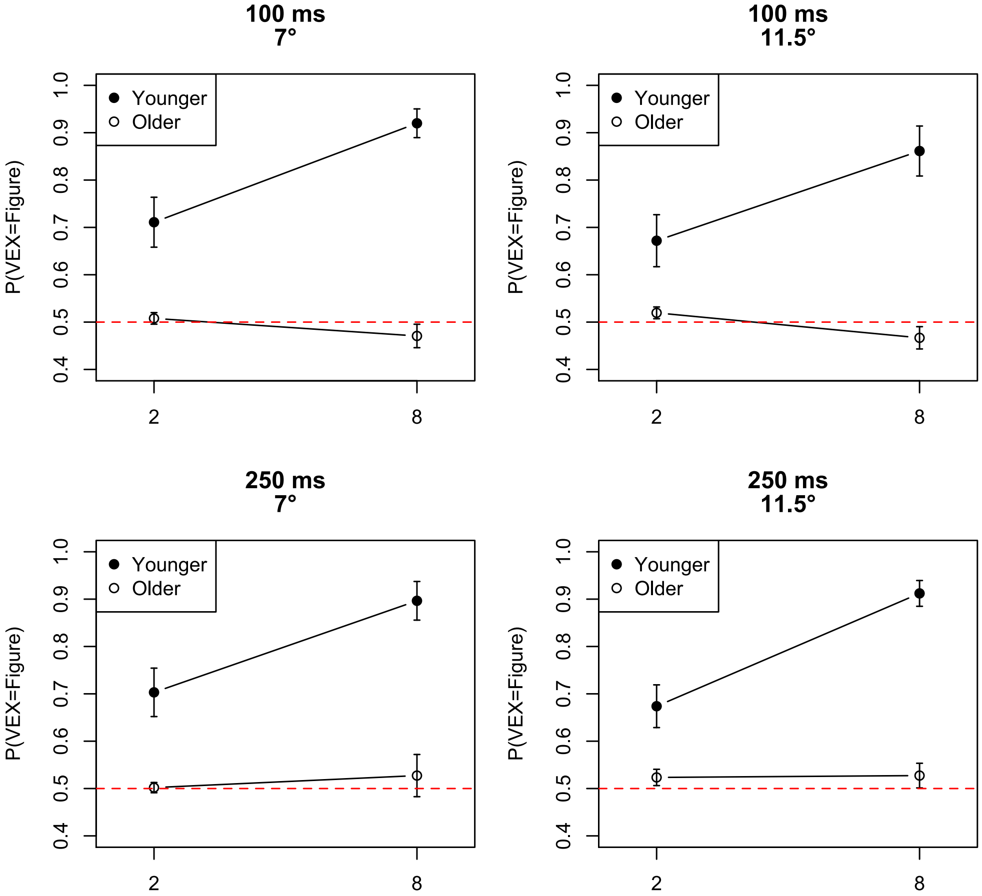

Figure 5. The results of Experiment 3 shown for each age group and each combination of stimulus duration and size. Each graph plots the mean proportion of trials on which VEX regions were perceived to be the figure in the 2- and 8-region stimuli. In all conditions, younger observers exhibited strong CCEs whereas older observers exhibited very small or zero CCEs. Error bars represent ±1 *SEM*.

### *Procedure*

The same methods and task used in Experiment 1 were employed in the current experiment, with the following changes. The current experiment used two stimulus size conditions (i.e., *large* and *small*). Large stimuli were the same size used in Experiment 1 and subtended 5.4° in height with a mean width of 2.5° and 11.5° for 2- and 8-region stimuli, respectively. Small stimuli subtended 3.3° in height with a mean width of 1.5° and 7.0° for 2- and 8-region stimuli, respectively. The viewing distance was 96 cm.

The experiment employed a 2 (stimulus size: large vs. small) × 2 (stimulus duration: 100 vs. 250 ms) × 2 (region number: 2 vs. 8) × 2 (age group: older vs. younger) design. This design allowed us to examine whether the age × CCE interaction depends on the effects of stimulus size, stimulus duration, and the interaction between size and duration.

Eight different orders were created by dividing each factor, duration, size, and region number, into two suborders, namely: 100 ms or 250 ms first; large or small first; and 2- or 8-region first. The suborders were then crossed, resulting in eight conditions in which sequential blocks always alternated between the 2- and 8-region conditions. Each participant within an age group completed the task according to a different order, with all 8 orders completed across all participants within each age group. Each condition involved 64 trials; stimuli were not repeated within conditions but were repeated across conditions.

## Results

The results are plotted in Figure 5. An ANOVA revealed significant main effects of age group, $F(1, 14) = 57.78$, $p < 0.0001$, $partial\ \omega^2 = 0.70$, and region number, $F(1, 14) = 14.03$, $p = 0.0022$, $partial\ \omega^2 = 0.35$. The interaction between age group and region number, $F(1, 14) = 18.80$, $p = 0.00068$, $partial\ \omega^2 = 0.43$, was significant. Follow-up tests indicated that the effect of region number was significant in younger $F(1, 7) = 20.30$, $p < 0.01$, $partial\ \omega^2 = 0.45$, but not in older observers, $F(1, 7) = 0.44$, $p = 0.53$. There was no evidence of a main effect of exposure duration, $F(1, 14) = 1.44$, $p = 0.25$, or an effect of stimulus size, $F(1, 14) =$

1.70, $p = 0.21$. The overall ANOVA also revealed a significant interaction between age group and stimulus size $F(1, 14) = 5.00$, $p = 0.042$, $partial\ \omega^2 = 0.14$. Subsequent tests found no simple main effect of stimulus size in older observers, $F(1, 7) = 1.10$, $p = 0.33$, but a marginally significant effect of stimulus size in younger observers, $F(1, 7) = 3.90$, $p = 0.089$, $partial\ \omega^2 = 0.10$, with higher P(VEX=Figure) for smaller stimuli. Younger observers reported perceiving VEX regions as figure more often than chance for all 2-region, all $ps < 0.017$, and 8-region conditions, all $ps < 0.0001$. However, older observers did not report perceiving VEX regions as figures more often than chance for either 2-region, all $ps > 0.16$, or 8-region stimuli, all $ps > 0.2$.

In summary, we found strong CCEs in younger but not older adults in all conditions, and the results did not support the hypothesis that age differences in CCEs was caused by a change in spatial integration or reduced ability to encode brief stimuli.

## Discussion

As in Experiment 1, younger observers perceived the VEX regions as figure more often than the CAV regions in both 2- and 8-region stimuli, whereas the CCE was not replicated in the older group. Contrary to the processing speed and spatial integration hypotheses, CCEs in seniors were not influenced by stimulus duration or stimulus size. In particular, we found no evidence that increasing stimulus duration, or decreasing stimulus size, increased the CCE in older observers. It is important to note that in this experiment, contrary to our observation in Experiment 1, the older group did not report seeing VEX regions as figure significantly more often than chance in any of the conditions, and the group did not show a significant CCE. However, this result is not unexpected given the small sample size used in Experiment 3 ($n = 8$) to replicate a weak CCE observed in the older group in Experiment 1 ($n = 24$). Given that a large proportion of the older group in Experiment 1 performed near chance (16/24 or 66%), it is not surprising that 7/8 or 85% of observers in this group were clustered around chance, and that performance dipped below chance in some conditions. Note that although some lines are trending in the opposite direction, the slope is not significant, so we interpret the lines as having an effective slope of 0.

These results demonstrate that neither the inclusion of stimuli that require less spatial integration (smaller visual angle), nor the increase of stimulus presentation time, nor the combination of the two, was enough to result in the emergence of a CCE in older observers. The results strengthen the suggestion that age-related differences are not limited by differences to low-level visual processes. But what then might cause this FG impairment in aging? Does the convexity bias/prior decline with age? This would be odd given that people are continuing to experience environmental regularities where the VEX side of a border is more likely to be the near side (Burge, Fowlkes, & Banks, 2010). Or is the absence of effects of convexity in older observers due to a failure to resolve the competition in BW displays? This seems like a reasonable possibility given the suppressive mechanisms underlying FG resolution (Cacciamani et al., 2015; Likova & Tyler, 2008; Peterson & Skow, 2008; Sanguinetti et al., 2016), and the evidence consistent with CCEs resulting from spreading of inhibition across HOM CAV regions (Peterson & Salvagio, 2008), the observation that increased competition stimuli require more processing time to resolve in younger observers (Salvagio & Peterson, 2010, 2012), and the findings of deteriorated cortical inhibition in aging (Pinto et al., 2010). The next experiment explores this *competition resolution* hypothesis by investigating whether older observers perceive VEX regions as figure more often when the competition in 8-region displays is reduced.

# Experiment 4

The results from Experiments 2 and 3 are inconsistent with the idea that the age-related difference in the CCE identified in Experiment 1 are due to age differences in spatial or temporal integration, and therefore raise the possibility that aging alters the competitive processes that are thought to be important for FG perception. Salvagio and Peterson (2012) suggested that suppression of competing, alternative interpretations of visual input is critical for successful FG resolution. If the efficacy of these suppressive processes is reduced by aging, then providing additional cues to reduce FG competition may increase the CCE in older observers. Experiment 4 examined this hypothesis by measuring CCEs with stimuli that consisted of regions that were colored in a way that aided FG organization by making it more plausible to perceive some regions as figures and others as ground.

Using stimuli like those illustrated in Figure 6, Peterson and Salvagio (2008) demonstrated that the heterogeneity or homogeneity of CAV region color modulates the CCE. They found that only when CAV regions were homogeneously colored, as in Figures 6A and B, did the CCE remain intact, presumably because HOM CAV regions are more likely than HET CAV regions to be a single surface, and this is therefore a requirement for perceiving CAV regions as a unified background (Goldreich & Peterson, 2012). However, whereas the CCE for BW stimuli could be abolished by

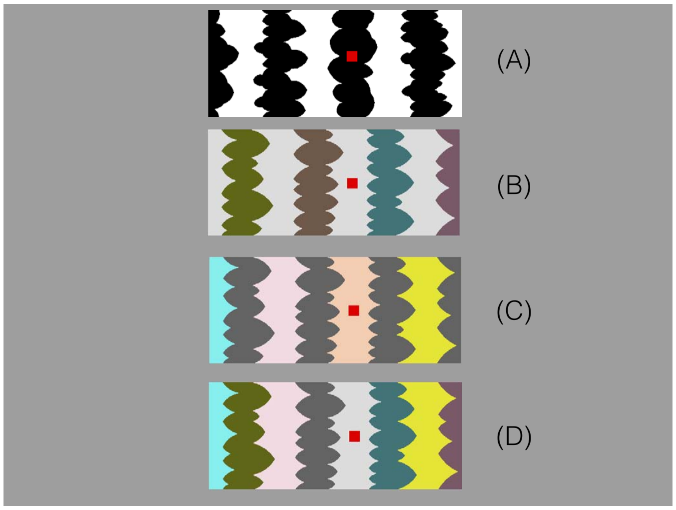

Figure 6. Four types of stimuli used in Experiment 4. (A) *Black and white* (BW), which were also used in Experiments 1 through 3. (B) *CAV-HOM/VEX-HET* (CavHom), which have HOM concave but HET convex regions. (C) *VEX-HOM/CAV-HET* (VexHom), which have HOM convex and HET concave regions, the reverse of CavHom stimuli. (D) Multicoloured displays, where both CAV and VEX regions are heterogeneously colored, thereby resulting in stimuli where each region is a different color.

backwards masking, requiring a stimulus-mask onset asynchrony (SOA) of 200 ms (Salvagio and Peterson, 2010), the CCE was maintained for CavHom colored stimuli even with SOAs as low as 100 ms (Salvagio & Peterson, 2012). These findings suggest that the HET color of VEX regions helped speed and/or strengthen resolution of alternative perceptual interpretations, enabling a more stable FG percept, because with HET VEX regions the alternative CAV = figure interpretation of the display is invalid (i.e., the color cue is inconsistent with a VEX = background scene). Hence, competition is reduced with CavHom stimuli (Figure 6B). Importantly, when VEX regions were homogeneously colored, as in Figure 6C, there was no reverse CCE effect (Peterson & Salvagio, 2008, 2013; Salvagio and Peterson, 2012). This suggests that the coloring of regions is not itself a FG background cue but rather that the visual system integrates convexity and color cues when resolving perceptual ambiguity in FG stimuli.

Here we examine whether the age-related decline in the CCE is related to seniors' inability to resolve an ambiguous percept through inhibitory processing that suppresses representation of regions likely to be ground. If age-related differences to this type of processing underlie the age × CCE interaction, adding an additional color cue to reduce the competition may support a CCE in older observers. Specifically, we hypothesized that using CavHom stimuli, which require less competition resolution, would enable the emergence of a strong region number effect in seniors.

## Methods

### Participants

Sixteen older ($M = 72.1$ years, $SD = 7.3$ years) and 16 younger ($M = 20.9$ years, $SD = 2.5$ years) observers participated in this experiment. All of the participants were compensated $10 for participating in the study, which took approximately 30 minutes to complete.

### Stimuli and task

The same task used in Experiments 1 through 3 was used here. However, for this study, all conditions used only 8-region stimuli. Stimulus size was the same as the small size from Experiment 3 (i.e., mean height of 3.1°, and mean width 6.6° at the viewing distance of 96 cm). The stimulus duration was 250 ms. The experiment used four classes of stimuli that varied in terms of *region type* (i.e., the homogeneity of both VEX and CAV regions): black and white (BW), CAV-HOM/VEX-HET (CavHom), VEX-HOM/CAV-HET (VexHom), and multicoloured (see Figure 6). As in Salvagio and Peterson (2012), colored stimuli consisted of several colors including high and low luminance tones of yellow, cyan, magenta, and gray. The luminance was HOM across CAV regions and across VEX regions, and luminance between CAV versus VEX were equal steps from the background gray. The average luminance of high luminance fills was 81.5 cd/m$^2$, and the average of low luminance fills was 24.5 cd/m$^2$.

### Procedure

The task was the same as in the previous experiments, and there were six practice trials with novel multicoloured stimuli before experimental trials. Stimuli were blocked by condition, and condition order was determined quasirandomly: Each participant was assigned to one of four groups that varied in terms of which condition was presented first, and the order of the three remaining conditions was randomized for each observer.

## Results

One older observer had a P(VEX=Figure) score of 0.03 in the CavHom condition, which was more than *3 SD* below the mean, meeting the exclusion criteria for experiments presented here. This observer's data were removed from the sample and not included in subsequent analyses.

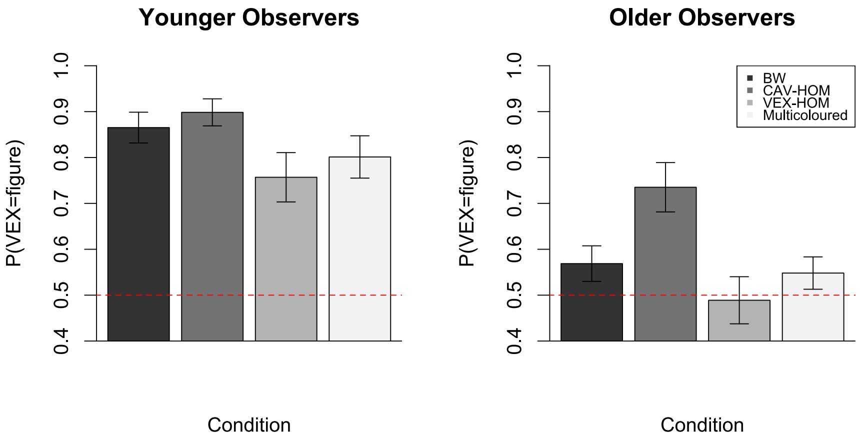

Figure 7. Proportion of stimuli where convex regions were perceived as figure for 8-region colored stimuli used in Experiment 4. Each bar shows the mean proportion of trials on which the VEX region was perceived as figure, i.e., P(VEX=Figure). Red dotted line represents chance performance. Error bars represent ±1 *SEM*.

Younger observers reported perceiving VEX regions as figure significantly more than chance with BW, $t(15) = 10.9$, $p < 0.0001$, CavHom, $t(15) = 13.5$, $p < 0.0001$, VexHom, $t(15) = 4.8$, $p = 0.00012$, and multicoloured displays, $t(15) = 6.5$, $p < 0.0001$. Within the older group, P(VEX=Figure) was greater than chance in the BW, $t(14) = 1.77$, $p = 0.049$, and CavHom, $t(14) = 4.4$, $p < 0.0003$ conditions, but not in the VexHom, $t(14) = -0.21$, $p = 0.58$, or multicoloured conditions, $t(14) = 1.4$, $p = 0.09$.

We analyzed the effects of adding color by conducting two planned linear contrasts. To assess the effect of reducing competition required to resolve displays, we first computed the difference between P(VEX=Figure) in the CavHom and BW conditions. This effect of reducing competition differed between age groups, $t(29) = 2.25$, $p = 0.032$, Cohen's $d = 0.81$, two-tailed. The difference score was significantly greater than zero in older observers, $M = 0.17$, $t(14) = 2.69$, $p = 0.008$, Cohen's $d = 0.61$, two-tailed, but did not differ from zero in younger observers, $M = 0.033$, $t(15) = 1.66$, $p = 0.12$, two-tailed. These analyses indicate that FG judgements made by older observers were more affected by the addition of color than were judgements by younger observers. Older observers showed a strong increase in P(VEX=Figure) when competition was reduced.

To assess the effect of CAV-region homogeneity, we compared P(VEX=Figure) judgments in conditions in which the CAV regions were HOM (CavHom + BW) to conditions in which they were HET (VexHom + multicoloured). We found that P(VEX=Figure) was higher in displays with HOM CAV regions, $t(29) = 4.73$, $p < 0.0001$, Cohen's $d = 1.40$, but that the effect of homogeneity did not differ between age groups, $t(29) = 1.21$, $p = 0.54$. These results suggest that both younger and older observers have a higher P(VEX=Figure) for HOM color grouping of CAV regions, compared to heterogeneous colors among CAV regions, replicating the requirement of homogeneity of color across CAV regions in emergence of the CCE (Goldreich & Peterson, 2012; Peterson & Salvagio, 2008).

These analyses are illustrated by Figure 7, which plots P(VEX=Figure) for each group and condition. In older observers, P(VEX=Figure) is significantly larger in the CavHom condition than the BW condition, and the difference between those two conditions is much larger in older than in younger observers. However, the difference between P(VEX=Figure) in the HOM and HET conditions is approximately the same in both age groups.

## Discussion

The results from our younger observers follow the same pattern as Peterson and Salvagio (2008): P(VEX=Figure) was greater for 8-region displays when the CAV regions were HOM (BW and CavHom) compared to when they were HET (VexHom and multicoloured) in younger and older observers. Critically, we also found that older observers reported seeing VEX regions as figure on a large percentage of trials, showing high P(VEX=Figure) with the addition of HET color cues to VEX regions while CAV regions were HOM, whereas this manipulation did not have significant effects in younger adults. This result supports the idea that when competition amongst alternate percepts is reduced, perception in older observers is indeed influenced by convexity. Importantly, the lack of a lower than chance P(VEX=Figure) with VexHom stimuli indicated that this strong convexity effect is not simply an effect of color. These results support the idea that age-related differences in CCEs for BW displays is, at least in part, the result of differential processing in that older observers have a reduced ability to complete FG resolution for high competition displays.

## General discussion

### Main findings

Younger observers show strong CCEs in the perceptual resolution of FG: The tendency to perceive VEX regions as figures increases with number of regions surrounding the border of interest (Peterson & Salvagio, 2008); see Figure 1 and Equation 1. We found that CCEs are significantly reduced in older observers. Furthermore, we found that age differences in CCEs are not affected significantly by manipulations to stimulus encoding time or spatial integration window (Experiments 2 and 3). However, we did find that older observers do exhibit robust convexity effects in conditions that reduced competition among different FG percepts (Experiment 4).

Our findings support the hypothesis that age differences in CCEs were due to perceptual organization processing differences across age groups, as opposed to being the result of basic visual differences in ability to encode briefly presented images or to spatially integrate information across large displays. More specifically, the finding that P(VEX=Figure) increases in older observers when CAV regions are HOM, and VEX regions are HET, supports the idea that the age differences observed with BW stimuli in Experiments 1 and 3 were the result of age differences in the ability to resolve the competition between alternative FG interpretations of those stimuli. The previous finding that younger participants perform at chance in all conditions, with no clear CCE, when poststimulus processing time is cut short by masking for BW displays, but not for CavHom displays (Salvagio & Peterson, 2012), demonstrates that resolution of competing perceptual interpretations entails more competition when alternative interpretations of the display (i.e., the CAV = Figure interpretation) are more valid. Specifically, competition between alternative perceptual interpretations of a stimulus is reduced when likelihood of VEX regions composing a unified surface is eliminated by using HET fills across VEX regions. However, the increased competition between BW alternative interpretations compared to CavHom stimuli that takes longer to resolve in younger adults cannot be resolved by older adults even with excess processing time (i.e., without masking). Yet, the reduced CCE in aging is largely overcome when competition is relatively reduced using HET VEX regions. Effectively, the removal of the conflicting VEX-HOM cue increases the ability of seniors to determine which regions most clearly align with figure or ground, so they can inhibit the ground regions.

The results reported here extend previous findings of impaired FG organization in older observers observed in a temporal structure paradigm (Blake, Rizzo, & McEvoy, 2008). Our results demonstrate age-related FG impairments using static stimuli, consistent with a recent report by Anderson, Healey, Hasher, and Peterson (2016) using different FG displays and showing impaired inhibitory competition in older adults. These findings are consistent with other age-related inhibitory perceptual effects (Betts et al., 2009) and, overall, support the notion that changes to inhibitory processing in aging affect FG perceptual organization. The hypothesis supported by this work may also provide a basic explanatory mechanism for more classical findings of altered FG perception in older observers. For example, Kline, Culler, and Sucec (1977) observed that older subjects were less able to reverse the initial FG organization of displays that had a preferred initial percept. Our current theory and findings would suggest that older observers had more difficulty inhibiting the initial percept to perceive an alternative percept because the inhibitory mechanisms required to achieve switching are dampened in aging. Similar reasoning may apply to difficulties older adults have in reversing other types of perceptually ambiguous stimuli (e.g., Basowitz & Korchin, 1957; Botwinick, 1962, 1965; Botwinick, Robbin, & Brinley, 1959; Heath & Orbach, 1963; Korchin & Basowitz, 1956).

Although observers were corrected for near and far vision, it is possible that observers not wearing progressive lenses may have had some residual blur for the test distances of 90–96 cm. To speak to this issue we examined the relationship between the CCE and three visual measures: near acuity, far acuity, and contrast sensitivity (Figure 8, left, middle, and far panels, respectively). As Figure 8 shows, there was a significant omnibus correlation between the CCE and near acuity, $r = 0.35$, $p = 0.016$, but no significant correlation between CCE and either far acuity, $r = 0.24$, $p = 0.10$, or Pelli-Robson Contrast Sensitivity, $r = 0.058$, $p = 0.70$. Critically, there also were no correlations between CCE and any of the visual measures within either age group, all $p$s $> 0.2$. The lack of association between these visual measures and CCE scores within age groups suggests that spatial resolution does not account for variation in performance on our task. The results from Experiment 4 provide additional evidence supporting this view. Specifically, older observers do show a clear CCE with CavHom stimuli, but not with BW or VexHom stimuli, even though all stimulus sets have the same edge characteristics. The fact that seniors are able

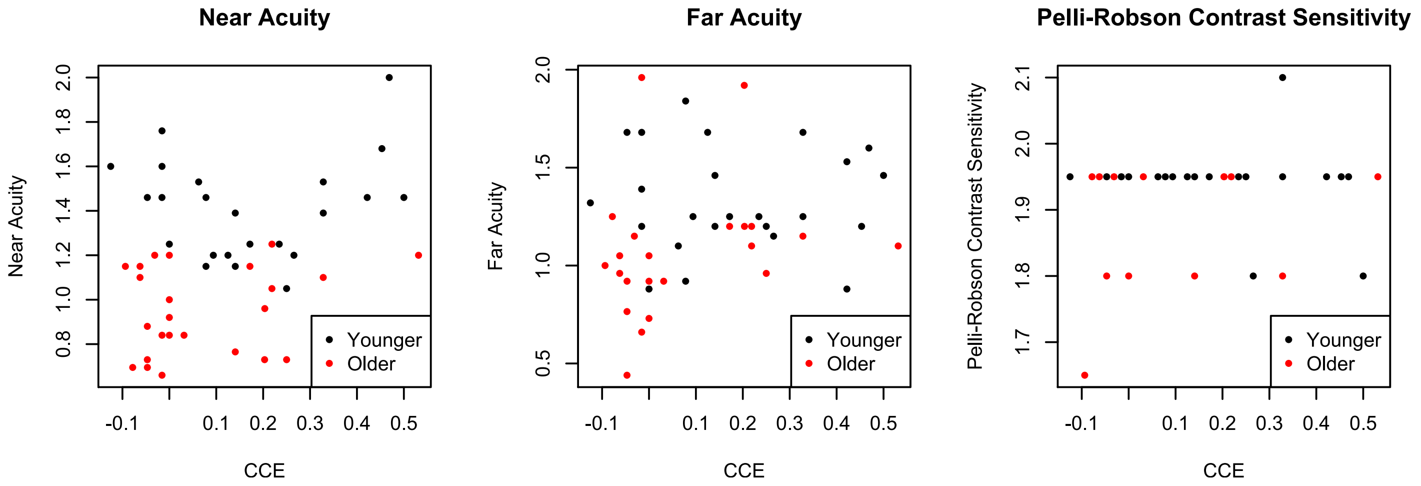

Figure 8. Scatter plots of individual visual measures as a function of CCE: near acuity (left), far acuity (middle), and contrast sensitivity (right).

to obtain a CCE in the CavHom condition further rules out the blur hypothesis.

## Questions and future direction

Having found an age difference in FG perception and demonstrating that age differences in the ability to resolve competition among alternative percepts accounts for much of the age effect, a number of questions remain.

First, is there a neural correlate associated with FG segregation that can explain individual differences in behavior within and across age groups to further our understanding of the way aging affects FG processing? At the cellular level in monkeys, border ownership cells in V1, V2, and V4 depend on FG organization of a contour passing through the receptive field of the cell (Zhou, Friedman, & von der Heydt, 2000). Therefore, we would expect the firing rates of older monkeys to be noisier and to less reliably encode the implied FG organization. We would also expect that, through manipulation of cortical GABA levels, reducing inhibition in younger monkeys to cause cell responses to resemble the pattern seen in older monkeys and that enhancing inhibition in older monkeys might cause cells to respond more similarly to those in younger monkeys. An examination of event-related potentials (ERPs) associated with presentation of convexity stimuli would yield insight into the temporal dynamics of FG processing and how these dynamics are affected by healthy aging in humans. Using stimuli that manipulated presence of a familiar shape on the ground-side of stimuli, Trujillo, Allen, Schnyer, and Peterson (2010) showed that the influence of this undetected cue was reflected in the P1 of the ERP. We might therefore expect the amplitude of the occipital ERP in the same time window to correlate with behavioral CCEs across individuals, age groups, and the contrast of high competition BW to lower competition CavHom stimuli. Nevertheless, it is possible that the time frame of the competition is different for displays that support CCEs than for the displays used by Trujillo et al. (2010). Another framework has linked alpha oscillations to suppression of perceptual input (Klimesch, Sauseng, & Hanslmayr, 2007; see also Payne & Sekuler (2014)) and recently indicated alpha power as an index of competitive FG processes (Sanguinetti et al., 2016). Given that alpha band power is reduced in healthy aging (Hong, Sun, Bengson, Mangun, & Tong, 2015), evoked alpha associated with CCEs is another potential neural correlate that might yield insight into the inhibitory processing underlying the CCE, its reduction in healthy aging, and the effects of reducing competition using CavHom displays. We are exploring these possibilities in ongoing research.

Second, how does aging affect the processing of other configural cues and the combination of multiple cues? As noted since the time of Rubin (1958), convexity is just one cue among many that influence FG organization. Comparing the way that different cues (for example enclosure, symmetry, and size), are affected by aging would further our knowledge of where impairments are cause for concern and where perception remains intact as a function of aging. Exploring the effects of combining multiple FG cues to modulate competition and ambiguity would yield further insight into FG segmentation of real-world stimuli. How could cues be combined to produce strong segregation in all the older observers? Are some older adults impaired in even highly unambiguous contexts? Are there specific cue-combinations or competition patterns that cause particular difficulties for older observers? A recent study (Froyen, Feldman, & Singh, 2013) demonstrated that the combination of convexity, motion, and accretion-deletion results in a novel percept of depth where VEX regions are perceived as rotating columns. Stimuli were similar in shape to those used in the current study with random-dot texture-filled VEX and CAV regions that drifted horizontally at equal speed but in opposite direction to each other. Accretion/deletion occurred at all region boundaries where the textures filling regions were terminating or being generated. This combination of configural, structure-from-motion, and background cues increases evidence that adjacent regions are separated in depth. Using such multicue stimuli would allow us to explore the question of whether the reduced CCE in aging reported here results in part from decreased presumption of three-dimensional character in the older group, which would reduce the CCE according to the Goldreich and Peterson (2012) Bayesian model of CCEs (Peterson & Salvagio, 2008). We are currently investigating this possibility.

Finally, from a more general perspective, it is important to ask this question: How do age-related differences in the ability to resolve FG assignment relate to real-world functioning? Although reduced competition resolution clearly has a significant impact on resolving convexity stimuli, how does this impact relate to segregating contours of real objects? And how does the overall pattern of FG age differences relate to individuals' ability to function in the real world? On one hand, it may be easy to imagine how the slowing of the processing that resolves a multi-region stimulus into an object that is occluding the adjacent background region could impact important functional activities like navigation and locomotion. For example, impaired FG organization could contribute to tasks that commonly affect older observers like compromised driving ability (Wood, 2002; Wood, Tyrrell, & Carberry, 2005), which requires rapid estimation of depth relations of multiple objects, and increased incidence of falls (Källstrand-Ericson & Hildingh, 2009), which could result from responding nonoptimally to slowly segmented objects, or from miss-assigning the depth order of a stair, curb, or convex obstacle. Recent findings that perceived depth in displays with binocular disparity are biased by border convexity (Burge et al., 2010) suggest that these are real possibilities. It is worth noting that some research on real-world depth and distance perception has failed to show age-related declines, with older observers even outperforming younger observers under some conditions (Bian & Andersen, 2013; Norman et al., 2015). However, such real world implications of FG organization in aging remain an open question, and one that is important in the study of how aging affects perception and how this relationship affects the lives of real individuals.

## Summary and conclusion

The studies presented above demonstrate reduced ability to use convexity for FG segregation in healthy aging. The effect is unlikely to be explained solely by lower level issues related to visual encoding, and deficits remain even for stimulus durations of 250 ms (with no mask) and for stimuli within area across which seniors can spatially integrate (Sekuler et al., 2000). Rather, the data presented here support the idea that the deficit in seniors is related to higher order processes that suppress irrelevant information, that lead to more plausible inferences in determining perceptual organization of ambiguous visual input.

*Keywords: figure-ground, aging, perceptual competition*

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