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Investigating the role of feature integration demands on attention efficiency.

Emma Kurtycz
University of Louisville

Investigating the Role of Feature Integration Demands on Attention Efficiency

By Emma Kurtycz

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Abstract

Feature integration and visual selective attention have been studied together to understand how we attend to different objects, often through conjunction search tasks. Conjunction search tasks involve searching for an object defined by multiple visual features in the presence of distractors. However, few studies have examined how different visual feature combinations impact search performance. Motivated by the functional and structural organization of the brain, this study investigated how differing feature combinations that theoretically place varying degrees of demand on feature integration impact attention efficiency. In two experiments, I explored reaction times (RT) and target detection sensitivity (d') across varying set sizes and visual feature conditions thought to systematically target distinct visual processing pathways in the brain (i.e., color-motion, luminance-motion, and shape-color). My findings revealed that across both experiments, RT increased set size, indicating that search becomes longer with more distractors present. In Experiment 1, color-motion had slower RTs compared to luminance-motion. In Experiment 2, color-motion was less efficient than luminance-motion in target-absent only trials and the addition of motion as a relevant visual feature was associated with decreased search efficiency. These findings provide a better understanding of why some objects may be easier to find or harder to ignore and allow us to place certain visual selective attention abilities along a spectrum of efficiency, depending on which visual features are the target of attention. Future studies should explore neuroimaging techniques to understand the role of neural connections on integration of visual features within and across visual pathways.

Lay Summary

Every day, we search for various objects, whether it is searching for our keys in a junk drawer or our phone on our messy kitchen table. Our ability to locate these items relies on how we process and combine the visual features that comprise them; for example, the shape and color of a phone. Different visual features are processed in different brain regions. For example, color and shape are processed in brain regions closer to one another, but further away from regions that process luminance and motion. With this in mind, I investigated how our ability to find an object among distractors would be impacted when that target object is defined by different visual feature combinations. To test this, I used a conjunction search task in which participants searched for a color-motion, luminance-motion, or shape-color target. As expected, I found that reaction time increases as the number of distractors increased. I also found that it took longer to locate color-motion objects compared to luminance-motion or shape-color objects. Additionally, finding moving objects took longer than finding stationary objects. These findings give us a better understanding of why some object may be easier to find than others and how motion plays a role in our search for objects.

Investigating the Role of Feature Integration Demands on Attention Efficiency

Whether running around our apartment searching for our phone while running late for class only to finding it sitting alone on our bedside table or digging through a junk drawer in search of a spare key, searching our environment for objects is an everyday occurrence. But why are some objects harder to find than others? Does standing still and scanning our apartment, rather than running around frantically, make it easier to find our phone? How does driving down the street impact our searching for a new restaurant? Decades of research have focused on visual search for static objects among various distractors (e.g., Wolfe, 2021), but to better understand how we search for objects in everyday situations, we must also understand how motion plays a role in our search of objects.

As we search for an object, we are also combining their visual features (e.g., shape, color) to form the whole object, a process called feature integration (Treisman & Gelade, 1980; Lynn et al., 2020, 2023). Feature integration plays an integral role in visual selective attention, which refers to the ability to attend to an object while ignoring other objects in the environment (Müller & Krummenacher, 2006; Lynn et al., 2023). The feature integration theory speculates the existence of two stages of attention when searching for an object. The first stage involves parallel, simultaneous processing of visual features (e.g., color, motion, luminance, etc.) in a visual field. The second stage involves the integration, or combining, of those visual features to form a whole object (Treisman & Gelade, 1980).

Another way of interpreting the two-stage process is along a spectrum of efficiency (Wolfe, 2021). Search efficiency refers to how quickly one is able to search for an object among an increasing number of distractors. The simultaneous, or parallel, processing stage of visual attention is thought to be efficient and can be seen in feature search tasks, where the object popsout (e.g., a red circle among green circles), regardless of the number of distractors. The integration processing stage of visual attention is thought to be inefficient and can be observed in a conjunction search task, in which searching for an object is slower with the addition of increasing distractors (e.g., a red square among green squares and red circles). Search efficiency can be represented with an RT search slope, which plots the change in reaction time (RT) as a function of distractor number. A steeper slope represents a less efficient search, where search takes longer as more distractors are added and, at its most inefficient, the search is completed serially. (Wolfe, 2021; Müller & Krummenacher, 2006). However, the impact of different visual feature combinations on search efficiency remains poorly understood.

Motivated by our understanding of where different visual features are processed in the brain, I argue that different visual feature combinations may be more or less demanding. Cortical visual processing begins in the primary visual cortex, V1. This visual information is then projected across two different visual pathways, the dorsal and ventral pathways (Mishkin et al., 1983; Milner, 2017). The dorsal pathway projects from V1 to areas of the posterior parietal lobe and is known as the "where/how" pathway as it supports visuospatial processing. The ventral pathway projects from V1 to areas of the temporal lobe and is known as the "what" pathway because it supports object identification (Cloutman, 2013). Different visual features are processed within these two pathways, with the ventral pathway processing color and shape and the dorsal pathway processing luminance and motion. However, there is evidence from macaque studies that suggests that color may also be processed within the dorsal stream (Thiele et al., 1999). In theory, integrating features that are processed within the same pathway (e.g., color and shape) should be more efficient than integrating features that are processed in separate pathways (e.g., color and motion), as the latter may require more cross-cortical connections between the two pathways. As such, the current study aims to examine how differences in feature integration demand impact visual attention efficiency in college-aged adults.

Attention and feature integration demand have been studied in older adults and Alzheimer's Disease (AD) patients and suggests that a notable loss of cross-cortical connections in AD impacts conjunction search for more demanding feature combinations. Both Festa et al. (2005) and Venkatesan et al. (2018) found that AD patients performed better on luminance-motion tasks compared to color-motion tasks. Venkatesan et al. (2018) found that the speed of search was slower in the color-motion condition, while Festa et al. (2005) found that more signaling cues were required in the color-motion condition to accurately determine the direction of a moving target. This points to how the loss of cross-cortical connections impacts the integration of color and motion in AD patients. In older adults, decreases in visual attention efficiency were evident during conjunction search but not feature search (Plude & Doussard-Roosevelt, 1989), while Agnew et al. (2020) found that decreases were evident in all attention tasks including conjunction and feature search tasks. These findings indicate that visual selective attention is impacted at the feature integration level in both elderly adults and AD patients.

Additional evidence of the importance of considering feature integration demands in the study of visual selective attention comes from child development research. Evidence suggests that feature integration in developing brains is not as efficient in moving across different visual pathways and improves with age, which may support visual selective attention development. Lynn et al. (2020) found that improvements in feature integration across childhood were greater in color-motion compared to luminance-motion conditions. Additionally, improvements in feature search and integration were connected to more improvements in search efficiency across childhood (Lynn et al., 2023). These findings indicate that throughout development between the ages of 4-10, feature integration is still developing and may be related to attention efficiency increases with age.

While feature integration in relation to attention has been studied in both aging adults and developing children, there is little research that looks at feature integration and attention in young adults, a time when the brain is in a relatively stable state. However, other studies have examined how young adults process moving objects in adulthood. Evidence suggests that young adults can filter visual space to attend only to moving objects and ignore stationary objects (Mcleod et al., 1991), and that cueing the direction of the moving target can make target search more efficient (Von Mühlenen & Müller, 1999). Sterzer et al. (2005) examined where in the brain the correspondence of an object defined by motion across two different visual frames, or snapshots of visual information, occurs. They found that the correspondence is processed in the calcarine cortex, or V1. Together, these studies suggest that attention to motion is established in adults, but there is still more to learn about the underlying mechanisms.

Evidence for feature integration in adults has been found with the redundant signals effect, which refers to the increased response to visual stimuli that are defined by redundant, or irrelevant, visual features (Poom, 2009; Miller 1982). For example, when searching for a red circle that also happens to be moving, there is an increased response seen by quicker reaction times. Additionally, using spatial cues to represent either rapid shifts in attention or split attention, Dowd and Golomb (2019) found that splitting attention resulted in greater errors when describing the feature (color and orientation) of the target, while shifting attention did not. These studies show evidence of feature integration through the redundant signals effect, as well as how the cuing of an object can impact how we integrate those irrelevant signals.

While set size is an important factor in evaluating search efficiency, another element that can be used is whether the target is absent or present. Target-absent trials typically take twice as long to complete when compared to target-present trials because, in target-absent trials, all objects need to be examined to confirm that the target is not actually present (Wolfe et al., 2010). The inclusion of both target-absent and target-present trials allows us to take a Signal Detection Theory approach to measure target detection. This is measured through the *d'*, or discriminability index, which considers hits (correctly indicating that the target is present) and false alarms (incorrectly indicating that the target is present when it is absent).

Together, the current literature has begun to describe the developmental process across the lifespan whereby feature integration improvements may support visual selective attention detection across childhood, and conversely feature integration disruptions may challenge visual selective attention in older adults, especially those with AD. However, little research has been done in young adults to investigate the role of feature integration demands on visual selective attention. As such, the current study investigates the impact of different feature integration demands on attention efficiency to further understand why it is easier to find some objects than others, allow for an overall placement of certain objects on the attention efficiency spectrum, and inform future neuroimaging studies that aim to understand how the brain supports visual selective attention across the lifespan.

In the current study, the reaction times of the conjunction search tasks were recorded, and the slope of the reaction times were used to determine attention efficiency among different conditions of distractor number and feature integration demand. The visual features that define the target were varied to place increasingly greater demand on feature integration. In addition to RT search slope, *d'* was used to measure target detection ability. Experiment 1 examined differing feature integration demands with two visual feature conditions, color-motion to represent across-pathway integration and luminance-motion to represent integration within the dorsal pathway. Experiment 2 sought to replicate and expand on Experiment 1 by including a third visual feature condition, shape-color, to represent integration within the ventral pathway. I predicted that, in college-aged adults, the search slope of the color-motion condition would be steeper compared to the slopes of the luminance-motion and shape-color conditions, indicating that processing across two visual pathways is less efficient than processing within the same visual pathway.

General Methods

Equipment and Calibration

The experiments were conducted on a desktop computer using MATLAB and PsychToolbox software. A NVIDIA Quadro FX 1800 and EIZO CG2420 ColorEdge monitor was used to present the search stimuli to participants. A photometer was used to measure luminance and color information that was then used to create a look-up-table to precisely control color and luminance stimuli with 10-bit precision.

General Procedure

Participants were asked to complete conjunction visual search tasks. Across all tasks, the order of the visual feature conditions was counterbalanced. Before beginning each search task, participants completed an instructional phase in which they were shown various stimuli and asked to identify one with a specific feature. For example, in the color-motion condition, they were asked to identify which square was red between a red and green square displayed on the monitor. This was done to verify that they were able to distinguish between the different stimuli. Once the instructional phase was complete, participants were asked to complete practice trials.

The set size conditions for the practice trials were randomly selected. Participants completed the practice until they understood what the task was and upon completion, began the task. During the search task, the fixation point was an orange cartoon clown fish ("Nemo"). For each visual search condition, half of the trials were presented with targets that were randomly placed at a target location out of 12 possible locations. Distractors were pseudorandomly added to the remaining locations, with one distractor required to be adjacent to the target. Participants had 3 seconds to search for each target before the next trial was presented. Two different audios played depending on if the participant correctly identified if the target was absent or present. Once a response was recorded or 3 seconds passed, the trial was terminated. Breaks were offered for 30 seconds after each trial block and 2 minutes after each visual feature condition.

In both experiments, set size and visual feature were manipulated. The set size conditions increased by increments of 2 and ranged from 1 to 11. The visual feature conditions differed between experiments and are outlined in their respective methods sections. For both experiments, the stimulus color values were taken from the look-up table generated when calibrating the monitor. The luminance of the red and green stimuli was matched, and the chromaticity of the black and white stimuli was matched. For each visual feature condition, the luminance contrast between the background and stimuli were equated.

Both experiments measured RT and accuracy for each trial. The accuracy of each trial was used to calculate hit rate, false alarm rate, and subsequently *d'*. *d'* was calculated using the loglinear approach, which involves adding 0.5 to the number of hits and false alarms and adding 1 to the total number of target-present and target-absent trials, before calculating the hit and false-alarm rate. This shifts the maximum value of *d'* from 3 to 3.5 (Stanislaw & Todorov, 1999).

Eyetracking data were also measured for each participant, however, it will not be used for the purposes of this study.

Experiment 1

Methods

Participants

This study included 25 undergraduate participants (*M* = 20.54 years, *SD* = 1.20 years; 19 female, 6 male) that were compensated with course credit. Participant's race make-up included 68% White, 24% Asian, 4% Multi-racial, and 4% "other". Participant's ethnic make-up included 80% non-Hispanic and 20% Hispanic.

Conjunction Search Task

In this experiment, participants completed several computer-based tasks including contrast sensitivity, feature search, and conjunction visual search tasks. For the purposes of this study, I will focus only on the conjunction search task. After each instruction phase, participants completed six practice trials, three in which the target was present and three in which the target was absent. Participants were told to "press the button as fast as you can when you see" a target and "don't press the button if you don't see" a target. Trials were terminated once a response was recorded or after 3 seconds. Each visual feature condition was presented in four blocks of 24 trials.

The stimuli presented were vertically or horizontally moving red, green, black, and white circles. The movement of the circles was oscillating at a speed of about $1° \times s^{-1}$ from its starting point about 0.5° in either direction. The circles were presented in one of 12 concentric locations equidistant from the screen center (approximately 8°). As mentioned before, the set size and visual feature for each task were manipulated. Two visual feature conditions were tested: color-motion and luminance-motion. The distractors for the luminance-motion condition were vertically moving white circles and horizontally moving black circles. The distractors for the color-motion condition were vertically moving green circles and horizontally moving red circles.

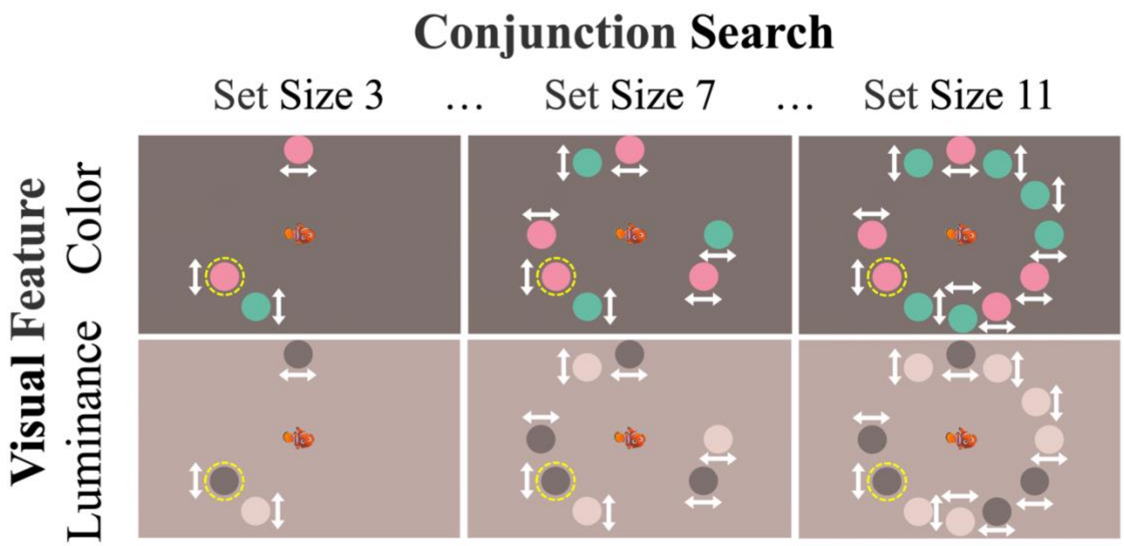

Figure 1. Illustration of conjunction search task conditions. Set Sizes 3,7, and 11 depicted. Not depicted: Set Size 1, 5, and 9 trials. Visual Feature conditions: luminance-motion and color-motion. Motion direction is depicted with the up-and-down (vertical) or left-and-right (horizontal) white arrows. Circles did not overlap during motion. Only target-present trials depicted. Yellow dashed circles = target (Source: Lynn et al., 2023)

RT and accuracy (correct hits of the button during target-present trials and correct rejections, i.e., no button press, during target-absent trials) were measured.

Results

Reaction Time

A linear mixed effects model was performed with visual feature and set size as fixed effects, participants and trial number as random effects, and RT as the dependent measure. The analysis was performed on all correct trials in which the target was present. My analysis revealed a significant effect of set size (Figure 1., F=1034.03, p=2×10^{-16}) and visual feature (Figure 1., F=5.10, p=0.014). To follow-up with the visual feature effect, I analyzed how RT differs between the two visual feature conditions. I found that RTs were significantly lower in the luminance-motion condition compared to the color-motion condition (*t*=-2.45, *p*=0.014). Additionally, I observed a trend that indicated that RT may have changed with set size differently between the two visual feature conditions ($p = 0.074$). As such, we performed post-hoc t-tests to determine the relationship between reaction times for each set size between the visual feature conditions. However, there was no significant difference between visual feature condition at any set size.

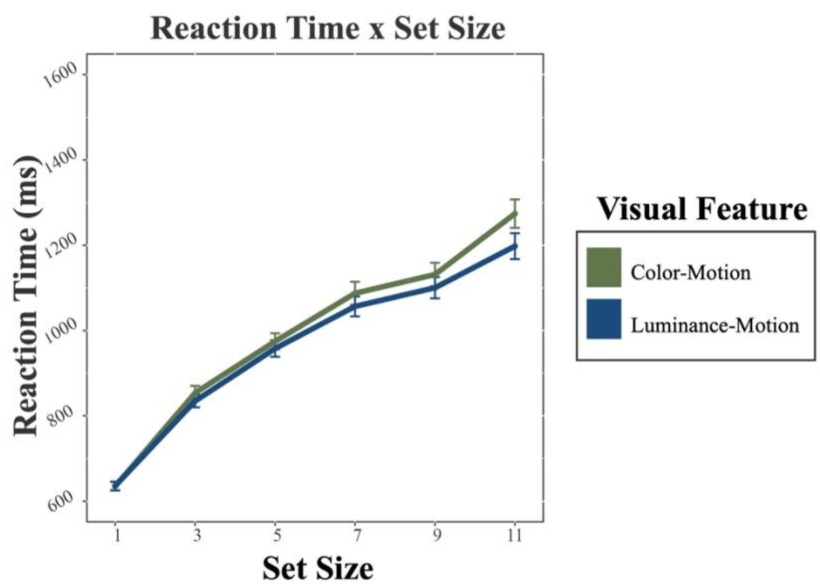

Figure 2. Average Reaction Time as a function of Set Size. The y-axis depicts Reaction Time from 600ms-1600ms. The x-axis depicts Set Size 1, 3, 5, 7, 9, 11. Two lines depicted, the green representing color-motion trials and blue representing luminance-motion trials. The color-motion line begin to diverge from the luminance-motion line as Set Size increases. Color-motion condition shows greater reaction times than luminance-motion.

d'

A linear mixed effects model was performed to analyze *d'* as a function of visual feature and set size. Visual feature and set size were fixed effects, participants were random effects, and *d'* was the dependent measure. As shown in Figure 3., there was no significant effect of set size (F=0.06, $p = 0.231$) or visual feature (F=0.24, $p = 0.622$) on *d'*.

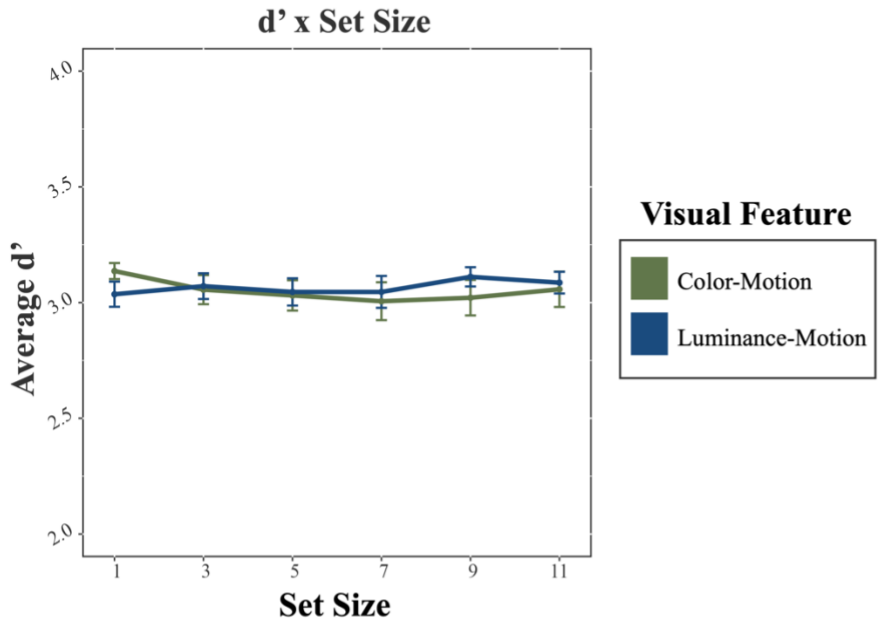

Figure 3. *d'* as a function of Set Size. The green line represents color-motion. The blue line represents luminance-motion. Y-axis depicts Set Size 1, 3, 5, 7, 9, and 11. No significant different between the two Visual Feature conditions.

Discussion

The purpose of this experiment was to examine how feature integration demands impact visual selective attention efficiency. I found that set size and visual feature did not impact *d'*, indicating that integration demand and number of distractors did not impact target detection abilities. However, I did find a significant effect of set size and visual feature on RT, where the luminance-motion condition had significantly lower RTs than the color-motion condition. These findings indicate that searching for an object defined by color and motion may be slower than searching for an object defined by luminance and motion. I also observed a trend-level interaction between visual feature and set size, where RT may have changed differently with set size between visual feature conditions. This interaction provides preliminary evidence that integration demands may affect search efficiency in young adults.

While this experiment provides us with an idea of how visual selective attention may be impacted by different visual feature combinations, there is still more to investigate. For example, how might RT change when you remove motion as a feature and integrate only within the ventral pathway? As such, in Experiment 2, I attempted to replicate these findings, with the addition of a third visual feature condition, shape-color. In this condition, participants searched for a red square among other green squares and red triangles. To preserve consistency between all conditions, every visual feature condition target was changed to a square (rather than a circle). This was done to keep the angularity consistent when searching between squares and triangles, whereas a circle may be easier to spot because its curves may stand out among the angles of squares and triangles. More trials were also conducted for a more reliable estimate of individuals' search abilities under these conditions. Additionally, I added a second button for the participants to press on target-absent trials.

Experiment 2

Methods

Participants

This study included 32 undergraduate participants (*M* = 19.05 years, *SD* = 1.07 years) that were compensated with course credit and had not participated in Experiment 1. Participant's race/ethnic make-up included 37.5% White, 18.8% Black or African American, 12.5% Multi-racial, 9.4% south Asian, 9.4% Hispanic, 6.3% Middle Eastern, 3.1% East Asian, and 3.1% Southeast Asian. Four participants were excluded: two due to incomplete data, one due to participant color-blindness, and one due to incorrect instructions followed. Thus, the final number of participants was 28.

Conjunction Search Task

In this experiment, participants completed only conjunction search tasks. Before completing the search task, they were asked to complete the demographic questionnaires and a Waggoner color blindness test.

Once the questionnaires were complete, participants were led into the testing room. The participants completed an instructional and practice phase for each Visual Feature condition, as outlined in the general procedure. Each practice phase had 4 trials. During the experimental trials, each visual feature condition was presented in four blocks of 48 trials (twice as many trials as Experiment 1). Participants were instructed to place their two pointer fingers on the “Z” and “M” keys of a keyboard and told them to press “Z” if they see the target and press “M” if they didn’t see the target.

Eyetracking data were also collected in this experiment using an infrared Eyetracking camara (EyeLink 1000 plus). The eyetracker measured movements of the right eye in each participant. Participants were instructed to place their chin in the chinrest, about 60 cm away from the testing monitor. This ensured that they kept their head still so that the eyetracker could measure their eye movements. Before beginning each visual feature condition, the eyetracker was recalibrated or revalidated.

The stimuli presented for the conjunction search task were red, green, white, and black squares and red triangles. The three visual feature conditions were color-motion, luminance-motion, and shape-color. The movement of the squares was either static or oscillating at a speed of about $1° \times s^{-1}$ from its starting point about 0.5° in either direction. The squares were presented in one of 12 concentric locations equidistant from the screen center (approximately 8°). In addition to visual feature, set size was also manipulated as outlined in the general procedure.

Trials were terminated once a response was recorded or after 3 seconds. RT and accuracy were recorded for each trial.

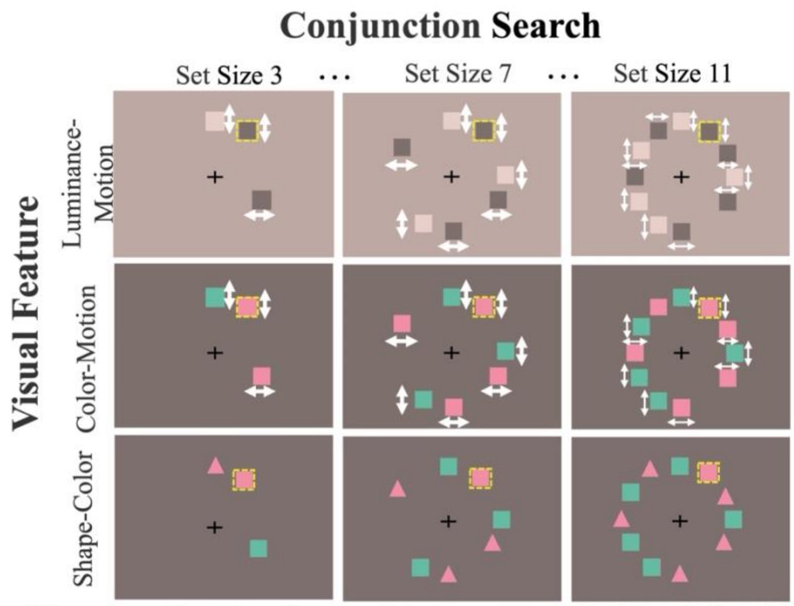

Figure 4. Illustration of Experiment 2 conjunction search task conditions. Set Sizes 3,7, and 11 depicted. Not depicted: Set Size 1, 5, and 9 trials. Visual Feature conditions: luminance-motion, color-motion, and shape-color Motion direction is depicted with the up-and-down (vertical) or left-and-right (horizontal) white arrows. Circles did not overlap during motion. Only target-present trials depicted. Yellow dashed circles = target

Results

Reaction Time

An omnibus linear mixed effects model was performed with visual feature, set size, and target presence as fixed effects, participants and trial number as random effects, and RT as the dependent measure. The analysis was performed on correct trials only. I found a significant effect of set size (F=4011.73, p=2×10^{-16}), visual feature (F=1859.97, p=2×10^{-16}), and target presence (F=124.41, p=2×10^{-16}).

To follow-up on the visual feature effect, I tested how RT differs between the visual feature conditions. I found that RT was significantly lower in the luminance-motion condition relative to the color-motion condition (t=-3.27, p=0.001) and RT for the shape-color condition was significantly lower than the luminance-motion condition (t=-37.52, p=2×10^{-16}). I also tested how RT differs between target-present and target-absent trials and found that reaction times for target-present trials were significantly lower than target-absent trials (t=-6.2, p=4.96×10^{-10}).

I also found a visual feature by set size interaction (F=318.71, p=2×10^{-16}), visual feature by target presence interaction (F=3.44, p=0.032), and a set size by target presence interaction (F=82.65, p=2×10^{-16}). To follow-up, I looked at how RT changed with set size between each visual feature condition. I found that RT significantly changed with set size for luminance-motion compared to color-motion (t=-3.63, p=0.00028) and for shape-color compared to luminance-motion (t=-16.51, p=2×10^{-16}). I also tested the interaction between set size and target presence and found that RT increased with set size at a lower rate for the target-present trials compared to the target-absent trials (t=-6.07, p=1.32×10^{-9}).

I completed a secondary analysis to examine how visual feature and set size impact RT in target-present and target-absent trials separately. For both analyses, I used a linear mixed effects model with visual feature and set size as fixed effects, participant and trial number as random effects, and RT as the dependent measure. For the target-present trials, I found a significant effect of visual feature (F=1067.84, p=2×10^{-16}) and set size (F=1552.39, p=2×10^{-16}), as seen in Figure 5 (b). I also found these effects in the target-absent trials, depicted in Figure 5. (a) (visual feature: F=827.76, p=2×10^{-16}; set size: (F=2522.79, p=2×10^{-16}). Further follow-up testing found that RT was significantly lower for shape-color compared to luminance-motion in both the target-present (t=-40.162, p=2×10^{-16}) and the target-absent (t=-36.66, p=2×10^{-16}) trials. Moreover, while there was no significant difference between luminance-motion and color-motion in target-present trials (t=-1.68, p=0.093), there was a significant difference in target-absent trials (t=-3.19, p=0.0014). I examined this further by testing for RT differences between luminance-motion and color-motion for each set size in the target-absent trials. I found a significant difference in RT between luminance-motion and color-motion for set size 11 in the target-absent trials (t=2.37, p=0.012).

I also observed a visual feature and set size interaction in both the target-present trials (F=183.52, p=2×10^{-16}) and the target-absent trials (F=144.19, p=2×10^{-16}). I tested this interaction further and found that RT changed with set size at a lower rate for shape-color compared to luminance-motion for target-present trials (t=-16.96, p=2×10^{-16}) and target-absent trials (t=-16.16, p=2×10^{-16}). In target-absent trials, RT for luminance-motion changed with set size at a lower rate compared to color-motion (t=-3.59, p=0.00033). This interaction was not evident in target-present trials (t=-0.97, p=0.33).

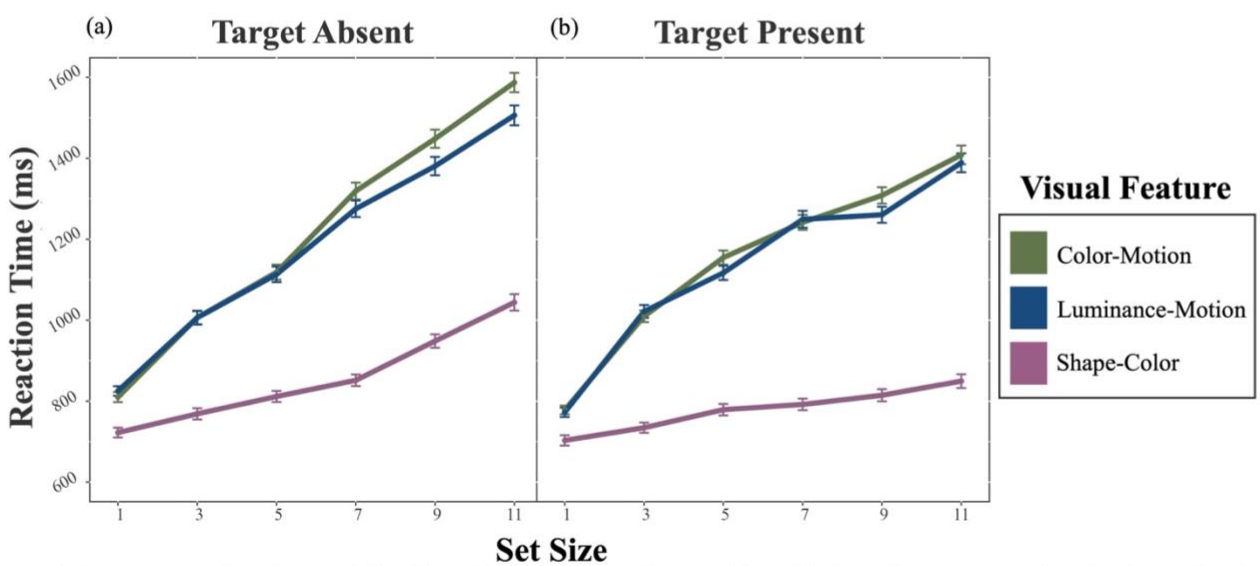

Figure 5. Average reaction time and Set Size. (a) Only target-absent trials with three lines representing the three visual search conditions. The shape-color (red) line is below the color-motion (green) and luminance-motion (blue) lines. Near Set Size 7 and beyond, the luminance-motion and color-motion lines begin to diverge. (b) Only target-present trials with the same representation of Visual Feature. Shape-color line is below the color-motion and luminance-motion lines

Next, I examined how target presence and set size impact RT within each visual feature condition separately. For all three analyses, I used a linear mixed effects model with target presence and set size as fixed effects, participant and trial number as random effects, and RT as the dependent measure. As seen in Figure 6., I found a significant effect of set size on reaction time in all three visual feature conditions: color-motion (F=2271.16, p=2.2×10^{-16}), luminance-motion (F=1955.49, p=2.2×10^{-16}), and shape-color (F=427.31, p=2.2×10^{-16}). I also found a significant effect of target presence on RT for all visual feature conditions: color-motion (F=33.86, p=6.27×10^{-9}), luminance-motion (F=21.53, p=3.57×10^{-6}), and shape-color (F=112.98, p=2.2×10^{-16}). Further testing found that target-present RTs were significantly lower than target-absent RTs in all three visual feature conditions: color-motion (t= -5.82, p=6.27×10^{-9}), luminance-motion (t=-4.64, p=3.57×10^{-6}), and shape-color (t=-10.63, p=2×10^{-16}).

Additionally, in all visual feature conditions, there was an interaction between set size and target presence, which indicates that RT changed with set size differently between the target-present and target-absent trials: color-motion (F=32.28, p=1.41×10^{-8}), luminance-motion (F=12.74, p=0.00036), and shape-color (F=61.81, p=4.57×10^{-15}). Follow-up analysis found that in all three visual feature conditions, RT changed with set size at a lower rate in the target-present trials compared to target-absent trials: color-motion (t= -5.68, p=1.41×10^{-8}), luminance-motion (t=-3.57, p=0.00036), and shape-color (t=-7.86, p=4.57×10^{-15}).

Further analysis was done for each visual feature condition to examine the differences in RT between target-absent and target-present trials for each set size. I found that there was a significant difference between target-absent and target-present trials in set size 1 for color-motion (t =1.92, p=0.054) and luminance-motion (t =3.21, p=0.0014), set size 7 for color-motion (t =2.78, p=0.006) and shape-color (t =2.95, p=0.003), set size 9 for color-motion (t =4.62, p=4.52×10^{-6}), luminance-motion (t =3.99, p=7.27×10^{-5}) and shape-color (t =5.96, p=3.63×10^{-9}), and set size 11 for color-motion (t =5.37, p=1.05×10^{-7}), luminance-motion (t =3.46, p=0.0006) and shape-color (t =7.33, p=5.52×10^{-13}).

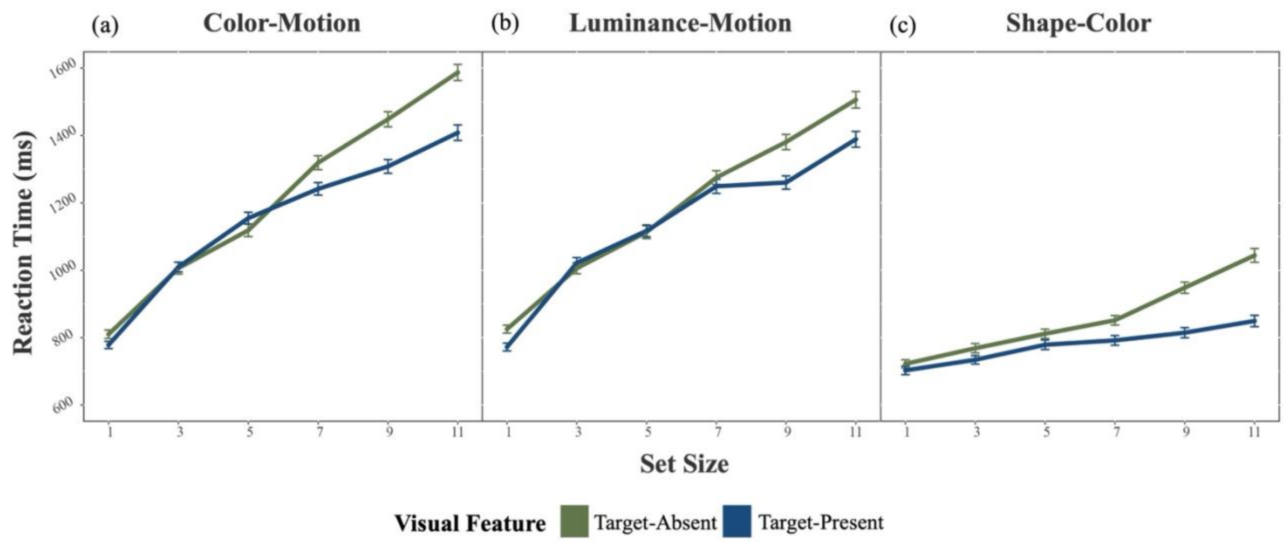

Figure 6. Reaction time and Set Size for each Visual Feature condition (a) Only color-motion trials. Green line depicts target-absent trials. Blue line depicts target-present trials. Lines begin to diverge from each other at Set Size 7. (b) Only luminance-motion trials. Lines begin to diverge from each other at Set Size 9. (c) Only shape-color trials. Lines are lower than in (a) and (b). Lines begin to diverge from each other at Set Size 7. The lines are not as steep as the lines in (a) and (b).

d'

Finally, I examined *d'* using a linear mixed effects model with visual feature and set size as fixed effects, participants as random effects, and *d'* as the dependent measure. I found a significant effect of visual feature (F=18.83, p=1.36×10^{-8}) and set size (F=53.55, p=1.10×10^{-12}), as seen in Figure 7. Further analysis examined how *d'* differed between visual feature conditions and found that *d'* was significantly higher in luminance-motion trials compared to color-motion trials (t =3.85, p=0.0001). I also found that *d'* in shape-color trials was significantly higher than luminance-motion trials (t =6.06, p=2.74×10^{-9}). Further examination of the set size effect tested how *d'* changes with set size in each visual feature condition separately. There was a significant effect of set size in the color-motion (F=47.41, p=1.82×10^{-10}) and luminance-motion trials (F=44.56, p=5.43×10^{-10}). However, set size did not have a significant effect on *d'* in the shape-color condition (Figure 7., F=0.25, p=0.617).

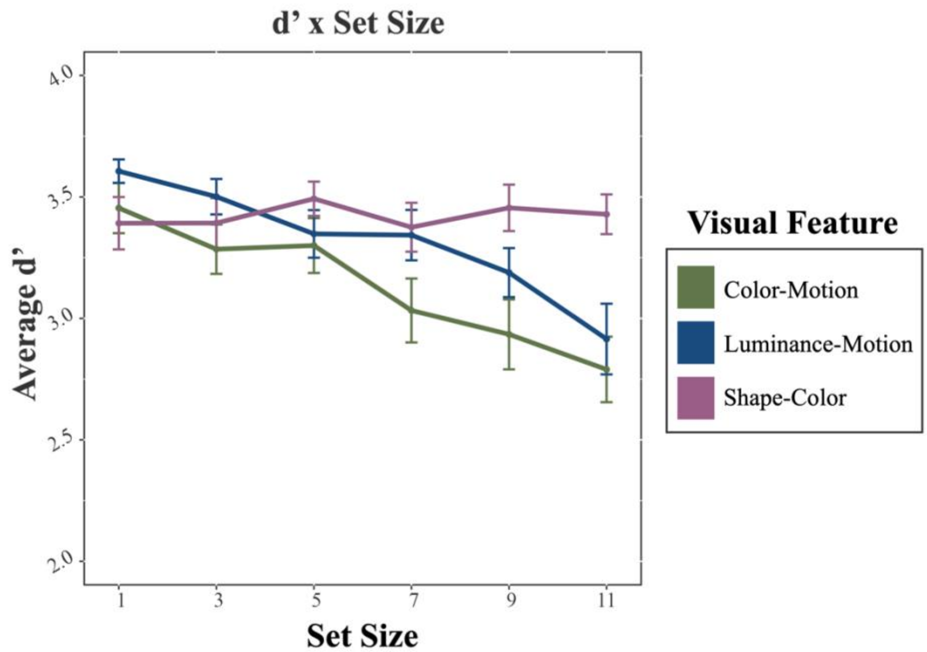

Figure 7. *d'* and Set Size. Three lines depict the Visual Feature conditions. The shape-color line (red) is flatter. The luminance-motion (blue) and color-motion (green) lines begin to diverge at Set Size 7.

Discussion

The purpose of this experiment was to replicate the findings of Experiment 1 and represent within-ventral pathway integration with the addition of a third visual feature condition, shape-color. This experiment successfully replicated the findings of Experiment 1, where reaction time increased with set size across all trials and the visual feature conditions had a significant impact on reaction time. I found that the overall RT search slope was steeper for color-motion compared to luminance-motion and luminance-motion compared to shape-color. However, upon further inspection, I found that RT search slope was only steeper for color-motion compared to luminance-motion in target-absent trials. This indicates that search is made less efficient only when the target is absent.

In our analysis of *d'*, I found overall main effects of visual feature and set size. This is not consistent with the findings of Experiment 1. Further investigation observed that *d'* was lower in the color-motion condition compared to luminance-motion, which indicates that in the color-motion condition, sensitivity for target detection decreases. Additionally, while there was an overall main effect of set size, set size did not have a significant impact in the shape-color condition. This can be seen in Figure 7, where the shape-color line is flatter than the luminance-motion and color-motion lines.

General Discussion

The current study aimed to examine how differing feature integration demands impact attention efficiency in young adults through conjunction search tasks involving color-motion (across-pathway integration), luminance-motion (within-dorsal integration), and shape-color (within-ventral integration) conditions and varying amounts of distractors. I found that 1) RT increased with set size across all visual feature conditions (Exp 1 & 2), 2) target-absent trials were less efficient than target-present trials (Exp 2), 3) the color-motion condition was less efficient compared to luminance-motion when targets were absent (Exp 2), and 4) the shape-color condition was the most efficient (Exp 2).

In both experiments and across all tasks, there was a significant effect of set size in which RT increased with set size. This indicates that the search is being done serially, and in turn, inefficiently, which is to be expected with conjunction search tasks (Wolfe, 2021; Müller & Krummenacher, 2006). This finding is in line with previous studies that have found that larger stimulus displays with more distractors resulted in increased reaction times (Beck et al., 2010). In our own lives, this could help explain why, when searching for an item in a drawer, we may take longer as there are more distractors to sift through.

My findings regarding target presence provides evidence that finding an object is more efficient than confirming that an object is absent. In Experiment 2, I found a significant effect of target presence across all visual feature conditions. Further investigation found that the target-present trials had faster RTs and flatter RT search slopes compared to the target-absent trials in all three visual search conditions. These findings are consistent with previous research that target-absent trials are twice as long as target-present trials (Wolfe et al., 2010) and point to how, in our everyday lives, we would find our keys in a drawer quicker if they are in the drawer compared to than verifying that they are not actually in the drawer.

I found evidence that the color-motion condition was less efficient than the luminance-motion condition when the target was absent, which supports the idea that differing integration demands may impact attention efficiency. Analysis of all correct trials in Experiment 2 showed that the luminance-motion condition had faster RTs compared to the color-motion condition. However, further investigation found that this was only the case in target-absent trials. Experiment 1 also found that luminance-motion RTs were quicker than color-motion, but in target-present trials. Furthermore, in Experiment 2, I found that the RT search slope of the color-motion condition was significantly steeper than luminance-motion in the target-absent only trials. However, in Experiment 1, the interaction between set size and visual feature on RT was observed to be a trend, rather than a full effect. These differences can be explained by the increased number of trials in Experiment 2, which provided a more reliable estimate of individuals' search abilities under these conditions, as well as the added response requirement for target-absent trials.

Another significant finding in Experiment 2 was that, in the color-motion condition, participants showed decreased sensitivity for target detection as set size increased compared to the luminance-motion condition. However, this was not observed in Experiment 1 for the same reasons mentioned above. Overall, these findings support the hypothesis that integration across both ventral and dorsal pathways makes search less efficient when compared to within-pathway integration. In conjunction with my RT findings, this effect may be more pronounced when an exhaustive search must be performed, as seen in the target-absent trials, and when the visual display becomes more complex as more distractors are added.

My findings illustrate that search for shape-color condition is more efficient compared to luminance-motion and color-motion. In all tasks, the reaction times for the shape-color condition were quicker and the RT search slope was not as steep as the luminance-motion condition, and subsequently the color-motion condition. Additionally, in the shape-color condition, *d'* was not impacted by set size, which indicates that as even as more distractors were added, sensitivity for target detection was not impacted. This demonstrates that searching for a static object may be more efficient than searching for a moving object. This could be explained by the nature of the search task, where time must be spent determining the direction of an object before identifying it as a target or a distractor. This must happen for every object until the target is found or target absence is confirmed. However, for the static shape-color condition, participants do not need to wait for the object to move and can discern target from distractor more efficiently.

One limitation of the study is the population that was sampled, which included only college-aged students enrolled in psychology courses and may limit the generalizability of these findings. Another limitation was the combination of visual features, where one combination of within-dorsal, within-ventral, and across-pathway integration was explored, but not all possible combinations. Future research should include a shape-motion or color-luminance task to understand the range of integration demands better. Additionally, the luminance and color contrast between the stimuli was controlled for using a photometer and look-up-table. As such, future research should match the luminance and color contrast on an individual level using flicker photometry. This study was also limited in the exploration of the cross-cortical connections occurring during across-pathway integration. Future studies should explore more about the cross-cortical connections using neuroimaging such as fMRI. This can help us further understand the role that these connections may play in the integration of certain visual features.

Conclusion

The current study investigated the impact of feature integration demands on attention efficiency and found that conjunction visual search for color-motion targets, theoretically requiring integration across the dorsal and ventral pathway, is less efficient when the target is absent than search for luminance-motion and shape-color targets, which theoretically require integration in only one pathway respectively. Additionally, the number of distractors impacted RT, demonstrating search takes longer when more distracters are present. Future research should include neuroimaging techniques to explore how cross-cortical connections play a role in integration across two visual pathways.

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