Attention Alters the Representational Geometry of a Perceptual Feature Space

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Abstract

Attention not only improves visual performance, but also alters the appearance of visual features, including contrast, spatial position, and color. We hypothesized that such effects could be accounted for by considering how attention affects the representational geometries of perceptual feature spaces. However, the effect of attention on the representational geometry of an entire perceptual feature space has not yet been characterized. Here, we conducted a psychophysical experiment to investigate how attention affects the representational geometry of orientation appearance by measuring how feature-based attention to a specific orientation changed the perceived similarities of oriented stimuli. Participants performed two interleaved tasks, consisting of an attention task requiring detection of small tilts in an array of bars in the attended orientation (±45º from vertical), followed by an independent triad orientation similarity judgment. We performed multidimensional scaling (MDS) analyses on the similarities estimated from the triad task under each attention condition, as well as when no attention task was performed. MDS revealed that a 3-dimensional solution best captured the representation of perceived orientations, and that attention increased the perceptual distances between orientations near the attended angle. This finding supports the idea that attention expands perceptual feature spaces to enhance the representation of task-relevant features.

Keywords: attention; representational geometry; psychophysics

Introduction

Visual attention enhances visual performance, as demonstrated by improved detection and discrimination of attended stimuli. These performance enhancements are accompanied by changes in the appearance of attended vs. unattended stimuli for perceptual features including contrast (Carrasco, Ling, & Read, 2004), spatial position (Suzuki & Cavanagh, 1997), and color (Chapman, Chunharas, & Störmer, 2023). These findings have motivated the hypothesis that attention alters the representational geometry of feature spaces (Chapman & Störmer, 2024), specifically to exaggerate the representational distances near an attended feature. However, the effect of attention on the representational geometry of an entire perceptual feature space has not yet been characterized. Here we asked how feature-based attention changes the representational geometry across orientation space.

Methods

Psychophysics Experiment

Participants (n = 7) completed the experimental task over several sessions. In attention sessions, participants completed trials that interleaved attention and similarity tasks. In similarity-only sessions, participants completed trials of the similarity task without any intervening attention task.

The attention task consisted of two spatially overlapping arrays of oriented bars (45° clockwise or counterclockwise from vertical). In separate runs of the task, participants were cued to attend to one array to detect small tilts in their orientation (individually thresholded for each subject and session). In the triad similarity task, participants judged which of two Gabors was most similar in orientation to a third, reference Gabor. Each orientation was randomly selected from the set of all possible combinations of 36 orientations (0-180°, 5° spacing).

Multidimensional Scaling Analysis

Similarity judgment responses were arranged into representational dissimilarity matrices (RDMs) based on the proportion of times participants judged a

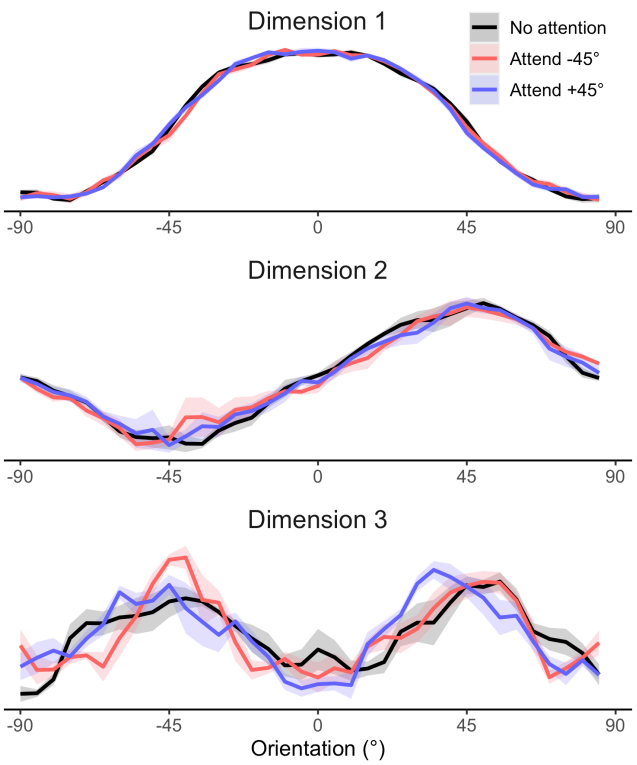

Figure 1: 3-dimensional MDS solution for each attention condition. Shaded region represents SEs.

particular pair of orientations as most similar. RDMs were constructed separately for runs in which attention was directed towards -45° or +45° orientations, and for similarity-only "no attention" runs. Non-metric multidimensional scaling (MDS) was performed on the RDMs for each participant and experimental condition, using *mdscale* in MATLAB. We examined the dimensionality of the data by comparing the stress of different MDS solutions and determined that three dimensions adequately captured the variance in similarity judgments. Individual MDS fits were aligned to the coordinate space of the grand mean RDM to enable visualization and comparison across conditions.

To assess how attention affected the representational geometry of perceived orientation, we calculated the "local length" of the curve by summing the Euclidean distance between each orientation in a 30° neighborhood around the attended and unattended orientations (Ringach, 2010). We compared the estimated lengths for each subject across attention conditions using a repeated-measures ANOVA, with follow-up t-tests to examine significant effects.

Results

To examine how attention affects the representational geometry of orientation, we compared the similarity

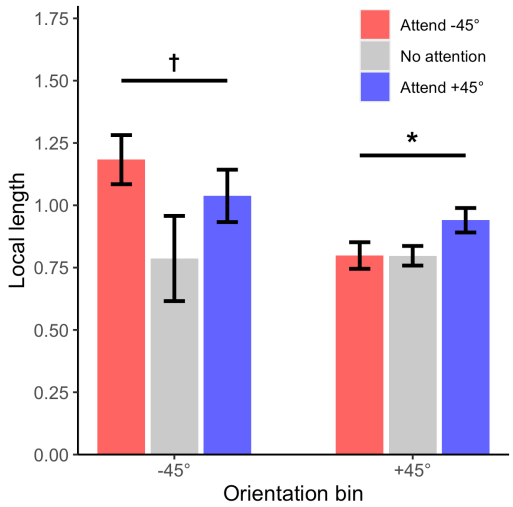

Figure 2: Mean local length of MDS solutions in the region around target and non-target orientations. Error bars represent SE. Significance reflects the main effect of attention for each bin, * $p < .05$, † $p < .10$,

judgments under different attention conditions using MDS. The observed 3-dimensional MDS fits (*Figure 1*) reflected key distinctions in orientation: 1) vertical vs. horizontal; 2) ±45° from vertical; 3) cardinals vs. obliques. To compare between attention conditions, we calculated the length spanned over orientations near the attended angles for each attention condition (*Figure 2*). We found that attention modulated the representational geometry, with a significant increase in length around +45° when attention was directed to that orientation ($p = .03$). A numerically similar pattern was observed around -45°, though this effect was not statistically significant ($p = .059$). While lengths were increased around attended angles, lengths around unattended angles were similar to the no-attention condition, suggesting that attention selectively expands the perceptual feature space. Thus, feature-based attention distorts the representational structure of the perceptual feature space for orientation, changing the perceived similarity between orientations.

Discussion

Our results support the hypothesis that attention can distort representational geometries in perception. By comparing the perceived similarity between orientations throughout the full feature space, we found that the representational space around an attended orientation was expanded, exaggerating the distance between orientations near the attended angle.

Attention has been shown to enhance perceptual discrimination as well as change the visual appearance of stimuli. Both of these findings can be explained within

the framework of representational geometry: increases in the representational distance between neighboring features supports greater discrimination performance, but also necessarily alters the perceived similarity between these features. Here, we examined, for the first time, the impact of attention on the global representation of orientation that was captured in participants' similarity judgments. Notably, we found selective effects on the distances near the attended angle, consistent with expansion of the representation around that point. However, we did not find any effects near the unattended angle (e.g., no contraction of the representation), despite previous behavioral and neural findings of suppression for unattended stimuli.

To explore the mechanisms underlying the changes in representational geometry we observe with attention, we are using computational modeling to determine how changes in neural gain, tuning position, and tuning width affect representational geometry, and which changes are consistent with our empirical observations. The representational geometry approach may allow us to develop richer links between neural coding and perception, and to understand how they might support adaptive changes related to attention.

Acknowledgments

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References

Carrasco, M., Ling, S., & Read, S. (2004). Attention alters appearance. *Nature Neuroscience, 7*(3), 308-313.

Chapman, A. F., Chunharas, C., & Störmer, V. S. (2023). Feature-based attention warps the perception of visual features. *Scientific Reports*, *13*, 6487.

Chapman, A. F. & Störmer, V. S. (2024). Representational spaces as a unifying framework for attention. *Trends in Cognitive Sciences.* Online proof.

Ringach, D. L. (2011). Population coding under normalization. *Vision Research, 50*, 2223-2232.

Suzuki, S. & Cavanagh, P. (1997). Focused attention distorts visual space: An attention repulsion effect. *Journal of Experimental Psychology: Human Perception & Performance, 23*(2), 443-463.