Biased competition in semantic representations during category-based visual search

Mohammad Shahdloo, Tolga Çukur

Introduction:

Humans are highly skilled at searching for object categories in their visual environment, and successfully dividing their attention among multiple target categories. In a recent study on category-based visual search, we have shown that attending to a specific category causes broad shifts in voxel-wise semantic tuning profiles to enhance the representation of the target [1]. However, little is known about the effects of divided attention on semantic representation across neocortex. Recent evidence suggests that in higher visual cortex response to two objects that are presented simultaneously can be described as a weighted average of the responses to individual objects presented in isolation, and that attention biases the weights in favor of the target object [2]. Here we question whether this biased-competition account explains attentional modulation of semantic representation during natural visual search for multiple categories.

Methods:
We conducted an fMRI experiment to test the predictions of the biased-competition hypothesis for semantic representations. Five human subjects viewed 25 min of natural movies containing 831 object-action categories, while performing three separate tasks in different runs: attend to “humans”, attend to “vehicles”, and attend to “both humans and vehicles” (i.e., divided attention). Whole-brain BOLD responses were recorded, and voxel-wise category models were fit separately for each task and in each individual subject [3]. To estimate a semantic space of category representation, principal components analysis was performed on voxel-wise category models pooled across the two single-target tasks. Semantic tuning profiles were then obtained by projecting category models for each task onto the semantic space. To test whether the tuning profile during divided attention can be described as a weighted average of the tuning profiles during single-target tasks ordinary least squares was used among tuning profiles for the three different tasks and a linearity index was quantified as the correlation between actual and predicted tuning profiles during divided attention. To reveal the interactions between the attentional bias in semantic tuning and the intrinsic category-selectivity of brain areas, the multi-voxel distributions of semantic tuning were examined. Specifically, the tuning distribution during divided attention was regressed onto the tuning distributions during the two single-target tasks. We then computed a shift index to measure the direction and magnitude of attentional bias in semantic tuning. This index shows the relative bias towards either of the two single-target conditions.

Results:
We find that the average linearity index is 0.49±0.03 (mean±s.d., averaged across subjects) in category-selective areas (FFA, PPA, EBA), and 0.56±0.02 in attentional-control areas (IPS, FEF, FO) (Figure 1). This result suggests that, in higher visual

cortex, a substantial portion of semantic tuning during divided attention can be expressed as a weighted average of tuning profiles during attention to single targets. By inspecting the shift index, we find that semantic representations in FFA, PPA and EBA are biased towards their preferred object category. Yet we found no significant bias in the attentional-control areas ($P>0.05$, Figure 2).

Conclusion:
These results suggest that the biased-competition theory provides a compelling account of attentional modulation of semantic representations during natural visual search for multiple target categories.

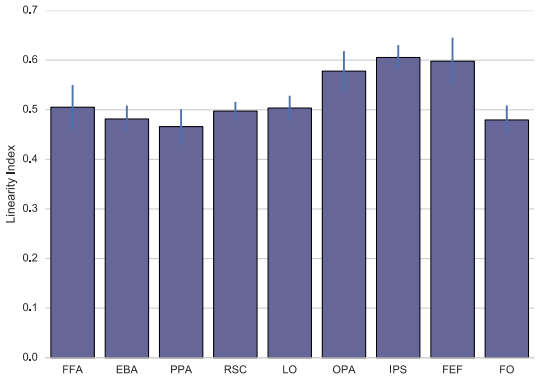

Figure 1: Linearity index in higher visual cortex (mean ± s.e.m. across subjects). The average linearity index in category-selective areas (FFA, EBA, PPA) was 0.49 ± 0.03 and the average linearity index in attentional-control areas (IPS, FEF, FO) was 0.56 ± 0.02, significantly higher than category-selective areas (t-test, $P<10^{-6}$).

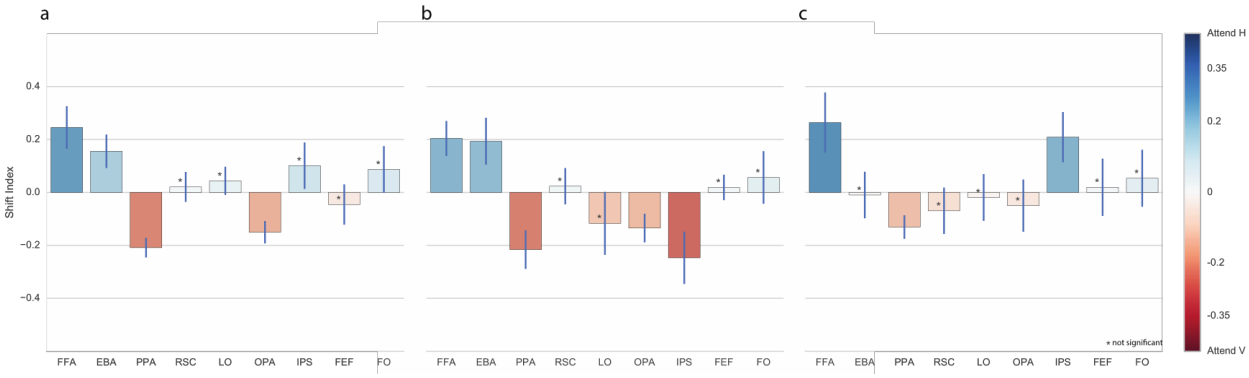

Figure 2: Shift index for semantic representation of **(a)** "target" categories, i.e. the average index for "human" and "vehicle" categories, **(b)** only "human" categories and **(c)** only "vehicle" categories. The shift index for a given category summarizes the bias in its semantic representation during divided attention. Bias towards the attend "human" condition is shown in blue color, and bias towards the attend "vehicle" condition is shown in red color. In FFA, EBA and PPA, semantic representation is biased towards the preferred object category.

References:
[1] Çukur, Tolga, et al. "Attention during natural vision warps semantic representation across the human brain." *Nature neuroscience* 16.6 (2013): 763-770.

[2] Reddy, Leila, Nancy G. Kanwisher, and Rufin VanRullen. "Attention and biased competition in multi-voxel object representations." *Proceedings of the National Academy of Sciences* 106.50 (2009): 21447-21452.
[3] Huth, Alexander G., et al. "A continuous semantic space describes the representation of thousands of object and action categories across the human brain." *Neuron* 76.6 (2012): 1210-1224.