Neuronal population decoding can account for perceptual lightness illusions

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Introduction

The relationship between the intensity of the light reflected from an achromatic object and how light the object appears depends on visual context. It has been difficult to relate this complexity to the activity of individual neurons, because neurons respond in varied ways to stimulus intensity. Here we ask whether a population decoding approach clarifies the neural underpinnings of perceived lightness.

Checkerboard Stimuli

- Stimuli were derived from Adelson's checker-shadow illusion, such that probe disks presented on checkerboard images were seen to lie either within a shadowed region ('shadow' condition) or within a luminance-matched region without a shadow ('no shadow' condition). Each corresponding check in the two image sets has the same average luminance.

Human psychophysics

Human psychophysical task

- Observers viewed the 'shadow' and 'no shadow' images side by side.
- A staircase procedure on probe luminance was used to find the point of subjective equality (PSE) for probes in each image type.

Human psychophysical results

- Subjects performed multiple interleaved staircases centered around different reference probe luminances. The resulting PSE values were fit and the intercept was calculated to quantify the magnitude of the perceptual illusion.

Monkey physiology

- Two 6x8 microelectrode arrays were chronically implanted in bilateral V4 in one animal (monkey J) and a 10x10 microelectrode array was implanted in V1 in the left hemisphere of a second animal (monkey B).

Monkey fixation task

- We varied the location and size of the stimuli during each recording session, but the stimuli were generally positioned such that the probe fell within the spatial receptive fields of the neurons we recorded.
- We analyzed data from experiments where the range of decoded intensities exceeded 0.2 for both 'shadow' and 'no shadow' probes, with probe intensities ranging from 0.2 to 1.0.

Monkey neuronal recordings

Single neuron responses to checkerboard stimuli are diverse

Population average responses do not obviously reflect perception

Decoding luminance from population responses

Leave one trial out regression to decode probe luminance using the population response

$$\text{Luminance} = \beta_1 r_1 + \beta_2 r_2 + \beta_3 r_3 \ldots$$

For the V1 example above: β_1 and $\beta_2 > 0$, $\beta_3 \sim= 0$

lum. = 20

r_n = [. . . . .]

shadow no shadow

Single session decoding results

Negative intercept values correspond to the case where the population decoded probe luminance as higher when it was placed in the shadow stimulus compared to the no shadow stimulus

Relating monkey neuronal responses to human psychophysical observers

Intercept values allow for direct comparisons between the physiology and psychophysical data

Conclusions

- Decoded probe luminances from V4 responses were consistently higher for the 'shadow' condition than those for the 'no shadow' condition. Moreover, there was a quantitative match between the psychophysical and neural effects.
- In contrast, although disk luminance could be decoded from the population of V1 neurons as accurately as from the V4 neurons, the V1 decoding differences were not in agreement with the perceptual illusion. This result suggests that the checker-shadow illusion arises at least in part from cortical computations.
- More generally, our data support the notion that decoding the responses of neural populations can shed light on the neural correlates of complex perceptual phenomena.

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