From neural codes to cognitive processes (part 1): Predicting human reaction time patterns from macaque neurophysiological data

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Abstract

As a first stage in linking neurophysiological data to cognitive processes, patterns of recognition reaction times (RT) in humans to different visual stimuli were predicted from neurophysiological data collected from the macaque superior temporal sulcus. Human subjects undertook a dual task paradigm consisting of an auditory task (odd/even judgement) followed by a mirror/normal judgement of rotated letters at high/low contrasts or large/small size. Consistent with predictions, there was a significant reduction in the effect of changes in stimulus contrast on RT at short versus long interval between the auditory and visual stimuli, while the effect of changes in stimulus orientation or size on RT was constant at different onset intervals. The predicted effects on response accuracy were also supported, including the observed increase in response accuracy with decreasing RT (the opposite of a speed~accuracy trade-off). Within a cognitive framework, the results suggested mental rotation and 'size normalisation' processes are 'central' whilst 'contrast normalisation' would be deemed, at least partially, a 'slave' process. Neural encoding in the visual system can therefore potentially provide an explanation of the seeming differences between 'central' and 'slave' cognitive processes by assuming that the 'decision-apparatus' reads the available input from the visual system.

Introduction

- We ask whether changes in neural response latency and response magnitude can be used to predict recognition reaction time and accuracy during a dual task paradigm.
- We assume that "executive processes" read the incoming neural activity and make decisions once a threshold has been reached (Perrett et al 1998).
- Stimulus contrast is signalled by changes in neuronal response latency and relatively small changes in response magnitude (Gawne et al. 1995; Oram et al. 1997; Wiener et al. 1998; Xiao et al. 2001)
- Other image transformations, such as changes in rotation, perspective view, size and part occlusion, cause little or no change in response latency but relatively large changes in response magnitude (Oram & Perrett 1992, 1994, 1996; Perrett et al 1998; Ashbridge et al. 2000).
- Neurophysiological data from the non-human primate was used to predict the effect of delayed monitoring of visual system responses on recognition reaction time (Figure 1) and accuracy (Figure 2).

Figure 1

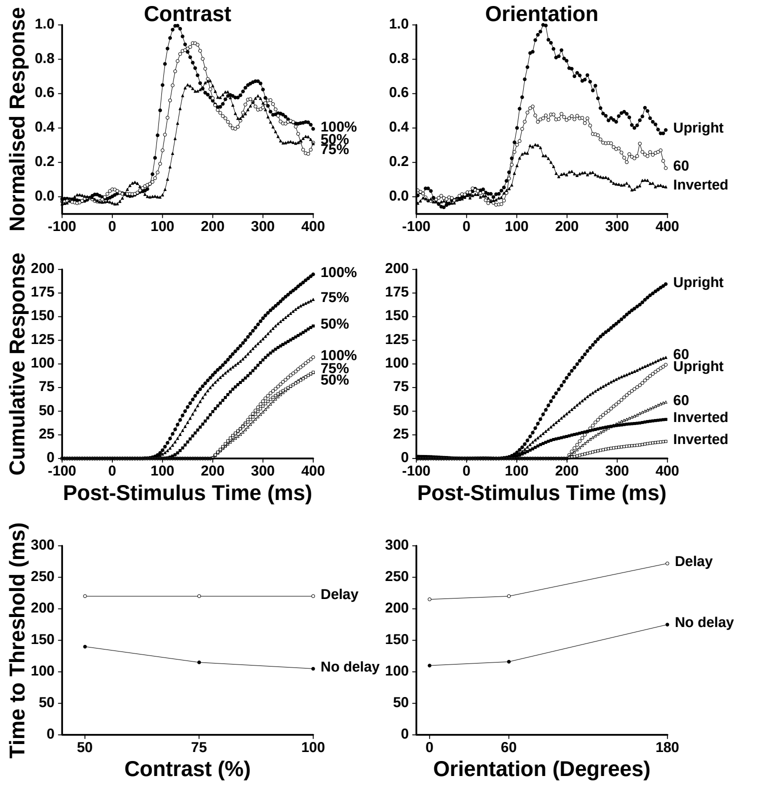


Figure 1. Predicting recognition reaction times from neural responses. Top Left: Population responses to stimuli of 100%, 75% and 50% contrast. The response latency varies with stimulus contrast. **Middle left**: The cumulative response of the above starting either from stimulus onset (time 0) or 200ms after the stimulus onset. **Bottom Left:** Time for the cumulative activity to reach a threshold of 10 spikes. **Top Right**: Population responses to three stimuli of different effectiveness. The responses have approximately the same latency but different magnitudes. **Middle Right**: Cumulative response to stimuli of three different levels of effectiveness starting either from stimulus onset (time 0) or 200ms after the stimulus onset. **Bottom Right:** Time for the cumulative activity to reach a threshold of 10 spikes.

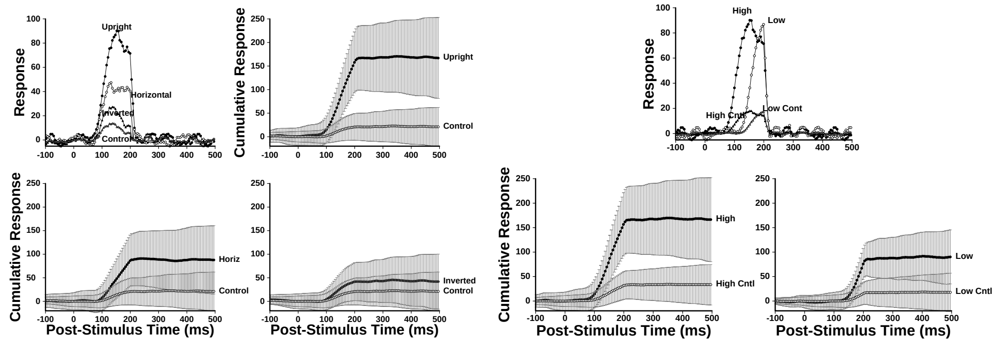


Figure 2. Schematic showing how accuracy levels are predicted from neural responses. To limit accuracy, masks were used. Thus responses would be curtailed by the mask. Within the threshold model, accuracy depends on the level of noise in the neural responses and the difference in response magnitude between the evoked responses to the presented stimulus (correct) and distracter stimuli (incorrect). [Actual accuracy estimates were estimated by simulating neural responses and determining whether responses to control stimuli or the actual stimulus crossed threshold first. Spike count distribution modelled as a truncated Gaussian (Oram et al. 1998). Envelope of response taken as average cell of STS (Oram & Perrett 1992). Spike times modelled using spike count matched model (Oram et al. 1999, 2001)].

Methods

Stimuli: Computer generated tone sequences (1-4 pips) were followed by the letters R and G in either their normal or mirror versions. The images were rotated 0^0, $\pm45^0$, $\pm90^0$, $\pm135^0$, or 180^0 from the upright. Each of the 32 images was presented either 0 or 1000 ms interval after the final pip (Immediate and delayed condition respectively).

Method: Participants had to make a judgement as to whether the number of pips was odd or even and then decide whether the image was the normal or mirror version. The response to the counting task was withheld until after the subject had made the mirror/normal response. After reaching criterion (70% correct, chance = 25%) subjects were given blocks of 192 trials with a subject controlled pause between blocks for 20 minutes.

Experiment A: The test stimuli were either high (>99%) or low (6%) contrast. Two high contrast stimuli were presented for each low contrast stimulus. Stimulus order fully randomised within blocks.

Experiment B: The test stimuli were either large () or small () size. Two large stimuli were presented for each small stimulus. Stimulus order fully randomised within blocks.

Experiment C: As experiment A, but instructed to respond as accurately as possible. Stimuli were masked (B/W checkerboard) after 50-200 ms (actual duration determined during practice session).

Experiment D: As experiment B, but instructed to respond as accurately as possible. Stimuli were masked (B/W checkerboard) after 50-200 ms (actual duration determined during practice session).

Results

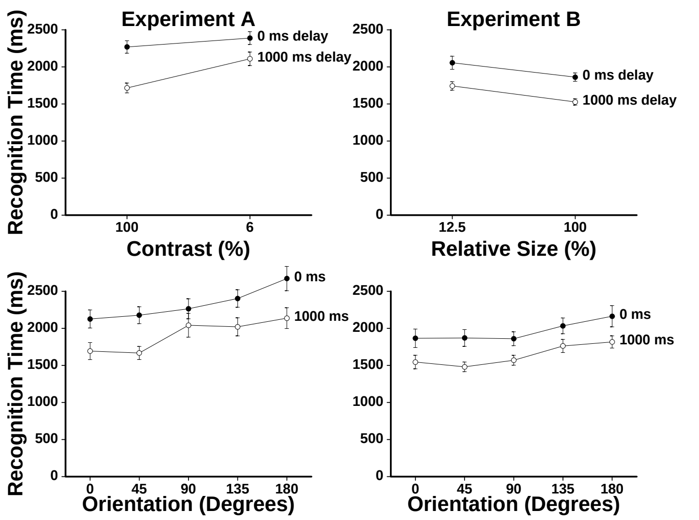


Figure 3. Mean RT (±SEM) is plotted as a function of stimulus manipulation. Upper left: Effect of stimulus contrast on RT. Decreasing stimulus contrast increased RT. The magnitude of the effect was greater when there was a 1000 ms interval between the auditory and visual stimuli. **Lower Left: Effect of stimulus orientation on RT.** The slope relating RT to stimulus rotation was highly significant and constant across the experimental conditions. [Overall analysis: Effect of stimulus rotation $F_{[4,60]}$=19.3, p<0.00005; Rotation by interval $F_{[4,60]}$=1.8, p>0.15; Rotation by contrast $F_{[4,60]}$=1.3, p>0.25; Rotation by contrast by interval $F_{[4,60]}$=3.5, p<0.02). Effect of stimulus contrast $F_{[1,15]}$=23.4, p<0.00005; Effect of interval $F_{[1,15]}$=58.0, p<0.00005; Interval by Contrast $F_{[1,15]}$=17.2, p<0.001]. **Upper Right: Effect of stimulus size on RT.** The effect of decreasing stimulus size was to increase the recognition reaction time by approximately the same amount regardless of interval. **Lower Right: Effect of stimulus orientation on RT.** The slope relating RT to stimulus rotation was highly significant and constant across the experimental conditions. [Overall analysis: Effect of stimulus rotation $F_{[4,68]}$=12.7, p<0.00005; Rotation by interval $F_{[4,68]}$=0.8, p>0.5; Rotation by size $F_{[4,68]}$=1.4, p>0.2; Rotation by size by interval $F_{[4,68]}$=0.9, p>0.4). Effect of stimulus size $F_{[1,17]}$=20.3, p<0.0005; Effect of interval $F_{[1,17]}$=19.3, p<0.0005; Interval by Size $F_{[1,17]}$=0.1, p>0.75].

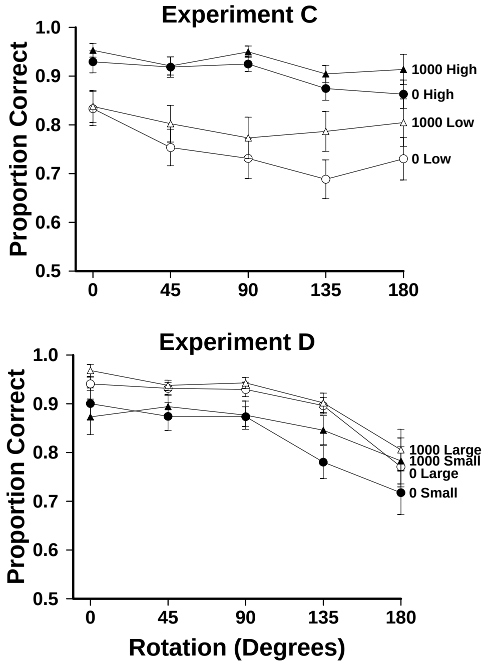
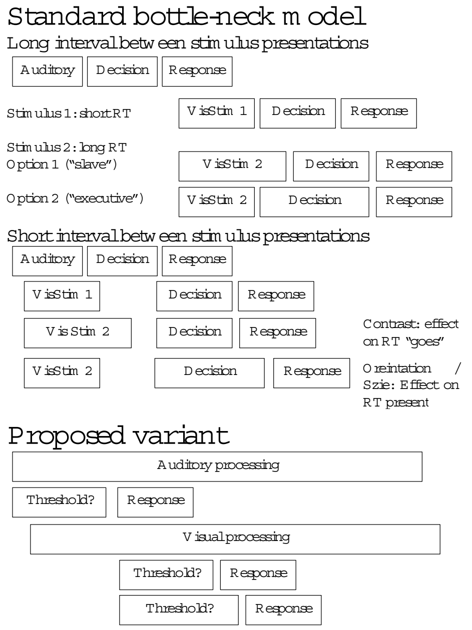


Figure 4. Accuracy decreases with increasing image transformation from "normal". Mean proportion correct (±SEM) is plotted as a function of stimulus orientation (0=upright, 180=inverted). Performance was well above chance levels (0.25) in all conditions. **<u>EXPERIMENT C.</u> Upper:** The overall accuracy decreases with increasing rotation, increasing interval and decreasing contrast. [Overall analysis: Effect of stimulus rotation $F_{[4,100]}$=6.6, p = 0.0001; Effect of stimulus contrast $F_{[1,25]}$=28.7, p < 0.0005; Effect of interval between pips and image presentation $F_{[1,25]}$=19.3, p = 0.0002; Rotation by contrast $F_{[4,100]}$=0.8, p > 0.5; Rotation by interval $F_{[4,100]}$=1.6, p > 0.1; Contrast by interval $F_{[1,25]}$=1.4, p > 0.25; Rotation by contrast by interval $F_{[4,100]}$=0.6, p > 0.6]. **<u>EXPERIMENT D.</u> Lower:** Accuracy also decreases with decreasing size. [Overall analysis: Effect of stimulus rotation $F_{[4,104]}$=10.7, p < 0.00005; Effect of stimulus size $F_{[1,26]}$=6.7, p < 0.005; Effect of interval between pips and image presentation $F_{[1,25]}$=6.7, p < 0.02; Rotation by size $F_{[4,104]}$=0.5, p > 0.7; Rotation by interval $F_{[4,104]}$=0.7, p > 0.5; Size by interval $F_{[1,26]}$=0.4, p > 0.5; Rotation by size by interval $F_{[4,100]}$=1.3, p > 0.2].



Standard bottle-neck model

Long interval between stimulus presentations
Auditory | Decision | Response
Stimulus 1: short RT: VisStim 1 | Decision | Response
Stimulus 2: long RT
Option 1 ("slave"): VisStim 2 | Decision | Response
Option 2 ("executive"): VisStim 2 | Decision | Response

Short interval between stimulus presentations
Auditory | Decision | Response
VisStim 1 | Decision | Response
VisStim 2 | Decision | Response — Contrast: effect on RT "goes"
VisStim 2 | Decision | Response — Oreintation / Szie: Effect on RT present

Proposed variant

Auditory processing
Threshold? | Response
Visual processing
Threshold? | Response
Threshold? | Response

Figure 5. Proposed change to bottle-neck models. The standard cognitive model used to explain the interactions between stimulus manipulation and ongoing tasks is the bottle-neck model (upper). The predictive power of neural responses suggests a simple change to these models (lower). Note that while the adapted model may not fit all data, the results indicate that the simplified model should be eliminated before accepting the traditional "slave" and "executive" process explanation.

Summary

- These results suggest a simple change to bottle-neck models should be considered (Figure 5).
- This experiment shows that neurophysiological data about neuronal encoding from non-human primates may predict human cognitive functioning.
- Dual task experiments that imply executive processes (e.g. mental rotation and size normalisation) may be a result of changes in the activation level within the slave system.
- Dual task experiments that imply slave processes (e.g. contrast normalisation) may be a result of changes in the activation latency within the slave system.
- Need to collect data from neurophysiological recordings in the macaque while the animal is performing similar dual task paradigms.