Neural dynamics of decision-making in an auditory delayed match-to-sample task

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Introduction

An important goal of research on the cognitive neuroscience of decision making is to produce a comprehensive model of behavior that flows from perception to action with all of the intermediate steps defined. To study the dynamic cortico-cortical interactions from perception to action, we connected a large-scale neurobiologically realistic auditory pattern recognition (APR) model to a finger-movement model through a three-layer decision-making model and performed an auditory delayed match-to-sample (DMS) task (Figure 1). In our DMS task, pairs of stimuli were compared, each stimulus being a sequence of three frequency-modulated tonal-contour segments, and a "match" or "non-match" button is pressed.

The APR model simulates neurophysiological activity of auditory and prefrontal cortex neurons during the performance of the DMS task (Figure 2, also see Poster B118, F132). An auditory-prefrontal network, whose neurons show a spectrum of transient and persistent activity during the delay period, computes the match likelihood response. Separate neural populations in a prefrontal-premotor network normalize the match likelihood response and encode time in their firing rate during the delay period. Next, the normalized responses are integrated with the output of the timing neurons and fed to a forced choice competitive network that performs action selection corresponding to match or non-match decisions. As the evidence for a match (or non-match) accumulates, the activity of the neurons in this competitive network increases until it reaches a threshold to initiate a motor signal that commands a virtual finger movement resulting in a match (or non-match) button press. The simulated response times and the different patterns of neural responses (transient, sustained, increasing) are consistent with experimental data and the simulated electrical activity provides insights into the neural interactions from perception to action in the DMS task.

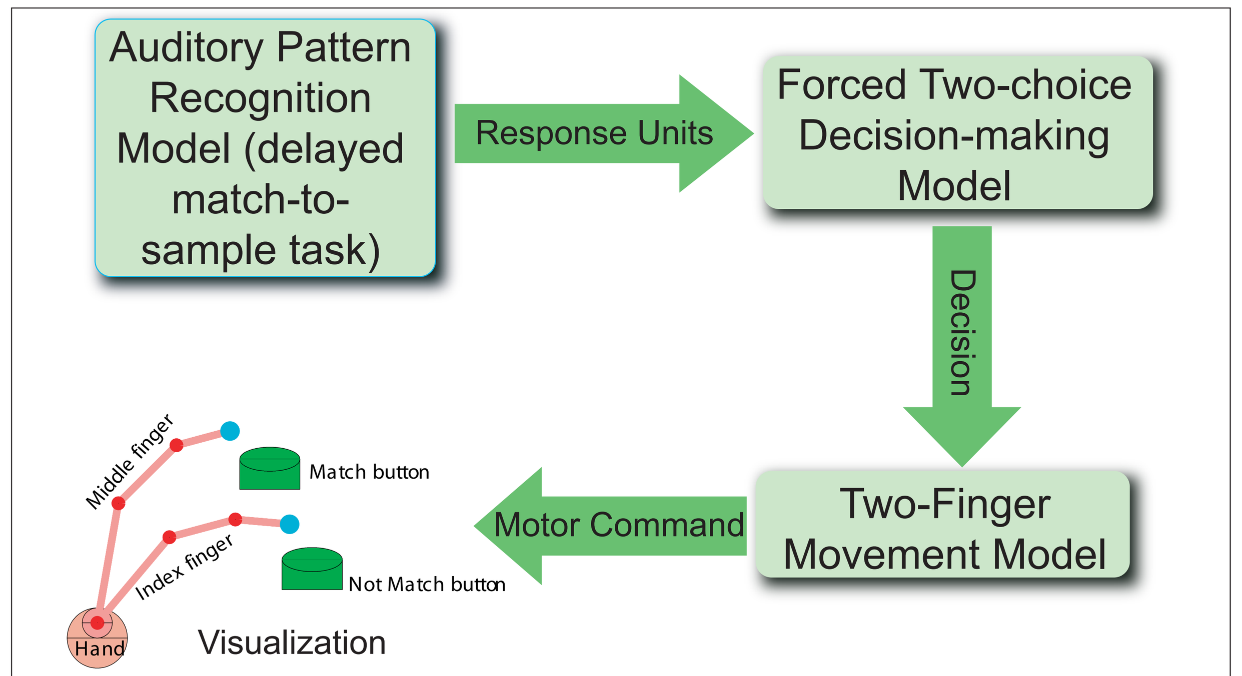


Figure 1. Connection of the three models

Auditory Model (Husain et al, 2004)

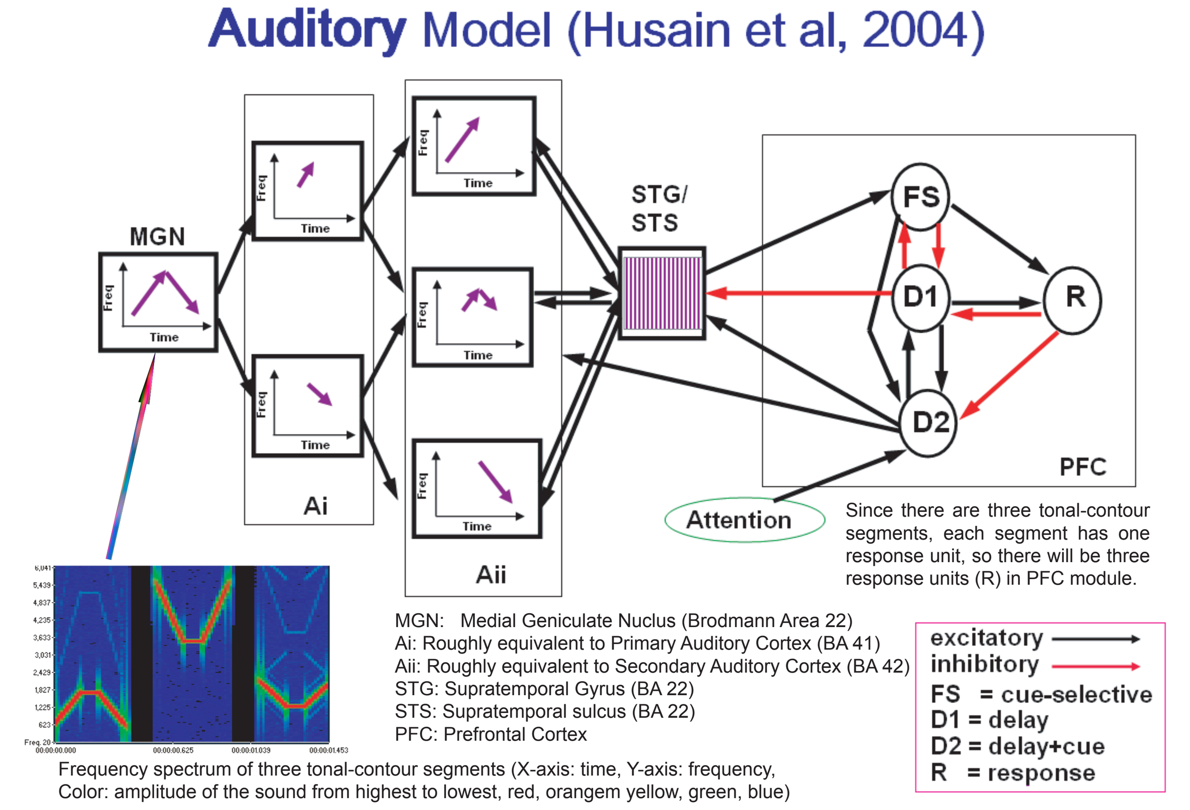


Figure 2. Auditory pattern recognition model

(* The auditory pattern recognition model in this figure omits the modules which handle the sequence complexity of the auditory stimuli. For detail, please see poster B118, F132.)

Method: decision-making model

The decision-making (action selection) model consists of four types of model neurons following a rostral-caudal organization. One neural assembly performs spatial integration and normalization of the response units in the auditory working memory network; whereas a second population encodes the time elapsed from the occurrence of the stimulus to be stored in working memory, and thus its activity increases with time. A third assembly integrates the normalized response activations and the timing signals to estimate match likelihood for each auditory segment. The final stage of this network, which is modeled as a forced choice competitive network, performs action selection and outputs the match or non-match decision. To describe this network, we use non-linear differential shunting equations plus a gaussian noise term.

First Layer:

Response integration and normalization

$$\frac{dx_i}{dt} = -x_i + (1-x_i)*[R_i(t) + f(x_i,\theta)] + noise, \quad i = 1,2,3 \;\; \ldots\ldots\ldots\ldots\ldots\; (1)$$

where $R_i(t) = \sum_{j=1}^{81} \frac{r_{ij}(t)}{\sum_{j=1}^{81} r_{ij}(t)} r_{ij}(t) = \sum_{j=1}^{81} w_{ij}(t) r_{ij}(t)$: weighted sum activity of subunits, ... (2)

$r_{ij}(t)$: activity of the j-th sub-unit in the i-th response unit at time t,

$$f(x,\theta) = \begin{cases} 10x & if\ x > \theta \\ 0 & o.w. \end{cases}$$: positive feedback function to current neuron.

Time Coding: $$\frac{dy}{dt} = \frac{1}{t_f} + noise \quad \ldots\ldots\ldots\ldots\ldots\ldots\; (3)$$

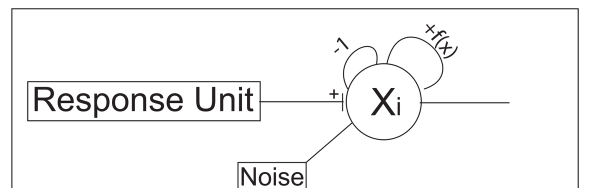


Diagram of the normalization neuron

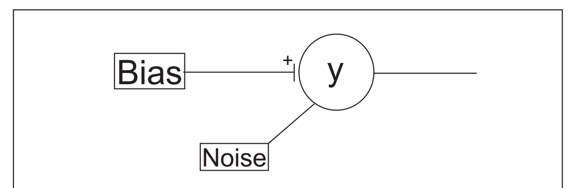


Diagram of the time coding neuron

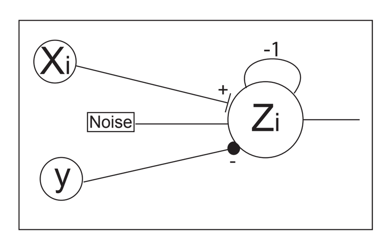
Second Layer:

Response-time integration:

$$\frac{dz_i}{dt} = -z_i + (3-z_i)x_i - (0.5+z_i)g(y,c_i,\sigma_i) + noise, \quad i = 1,2,3 \;\; \ldots\ldots\; (4)$$

where $g(y,c,\sigma) = \begin{cases} cy & if\ y > \sigma \\ 0 & o.w. \end{cases}$

Diagram of response-time integration ⟶



Third Layer:

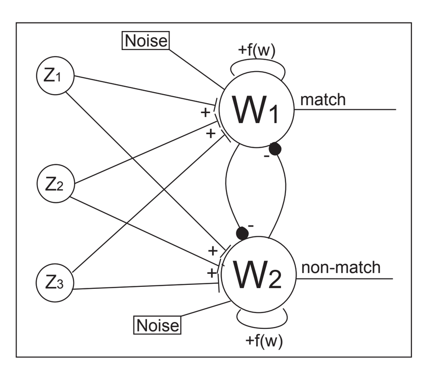
Action selection:

$$\frac{dw_i}{dt} = -w_i + (1-w_i)[\sum_{k=1}^{3} h_i(z_k^+) + f(w_i,\lambda)] - w_i f(w_j,\lambda) + noise \;\; \ldots\ldots\; (5)$$

where $h_1(z) = \mathrm{bz}$,

and $h_2(z) = \begin{cases} (1\text{-}z)/6 & if\ z > 0 \\ 3 & o.w. \end{cases}$

Diagram of action selection network ⟶



Note: The parameters in each equation were estimated from the training data set. The same parameters were used to validate the model using the test data set.

Table 1. Parameters for the system equations

Parameter	Value	Description
t_f (sec)	11.26	trial duration
θ	0.095	threshold of the feedback function for the normalization neuron
c_1	0.832	spectral timing: gains of the timing signal for each tone segment in the sequence of the tone stimuli
c_2	1.305	
c_3	2.3	
σ_1	0.6227	spectral timing: offset time for each segment divided by trial duration (e.g., 8.26/11.21 for last item)
σ_2	0.6798	
σ_3	0.7368	
b	0.635	gain for the "match neuron": larger b, faster decision of match
λ	0.5	threshold of the feedback function for the competitive network
γ	0.8	match or non-match decision threshold
Noise level		Gaussian random noise with mean zero, standard deviation 13% of the maximum neural activity (0.13*N(0,1))

Results

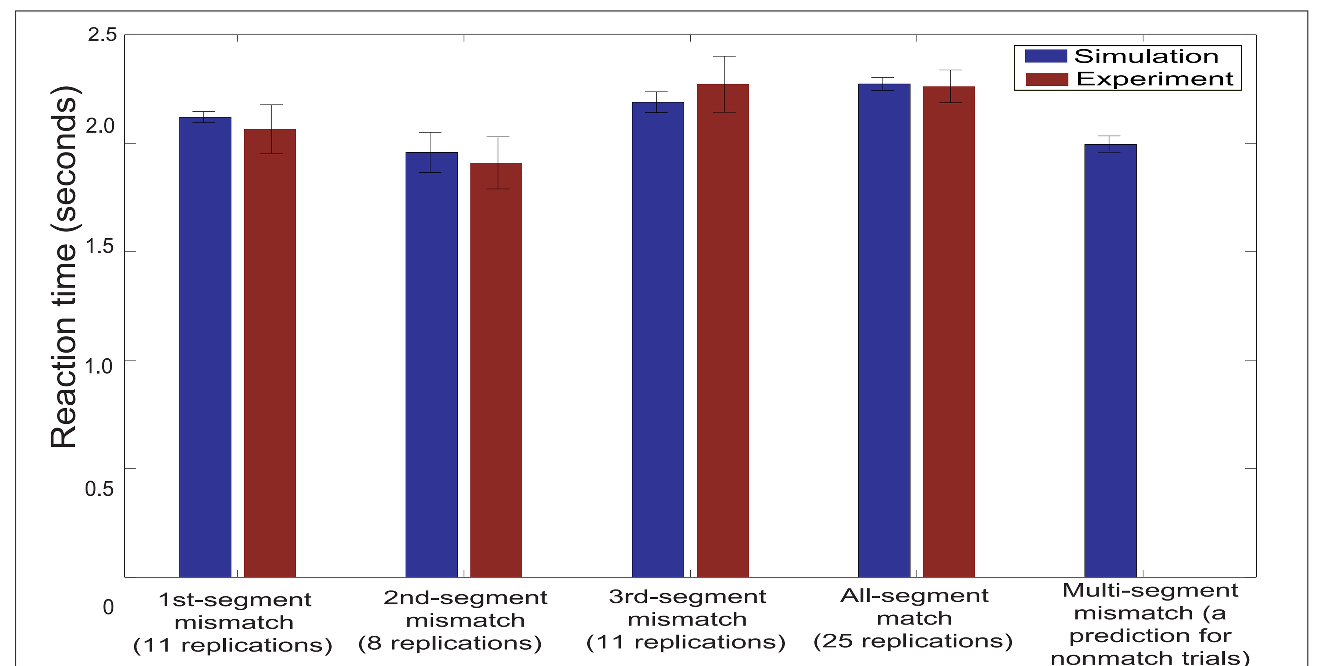


Figure 3. The simulated mean reaction time for either match or non-match groups are consistent with the experimental data (two-sample T-tests don't show significant difference between the simulated reaction times and the experimental ones. P-values are all greater than 0.56). The variation of the simulated reaction times depends on the magnitude of the noise level (also see parameter table of this poster).

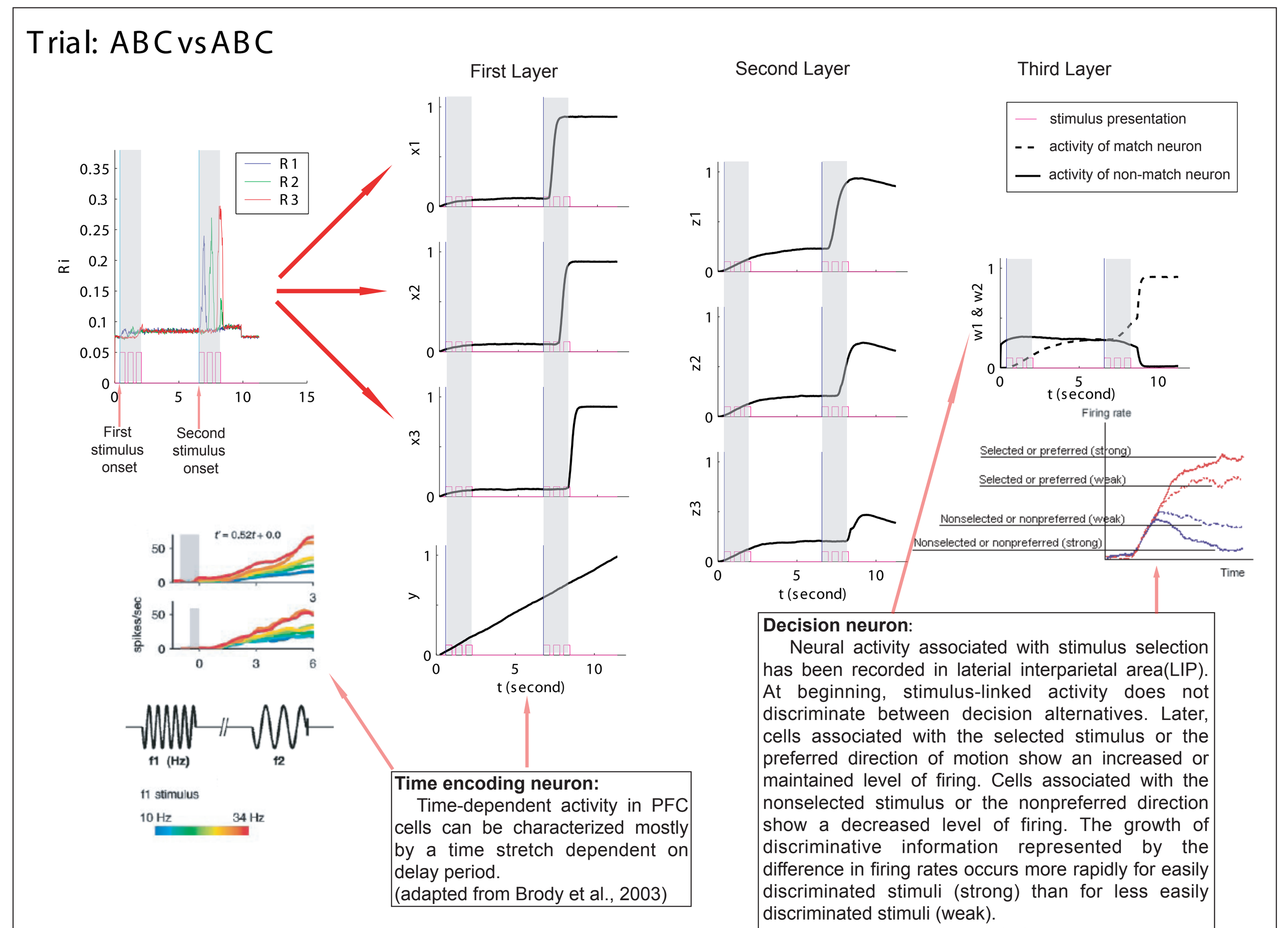


Figure 4. Neural activities of each neuron (from left to right) in the decision-making model for a typical match trial (the first tone stimuli is the same as the second stimuli) in the training data set. The plot of Ri shows the activities from the three response units of the auditory pattern recognition model. The Ri are the input to the decision making model. w1 and w2, the outputs of the competitive network in the last layer of the decision-making model, show that a "match" decision has been made.

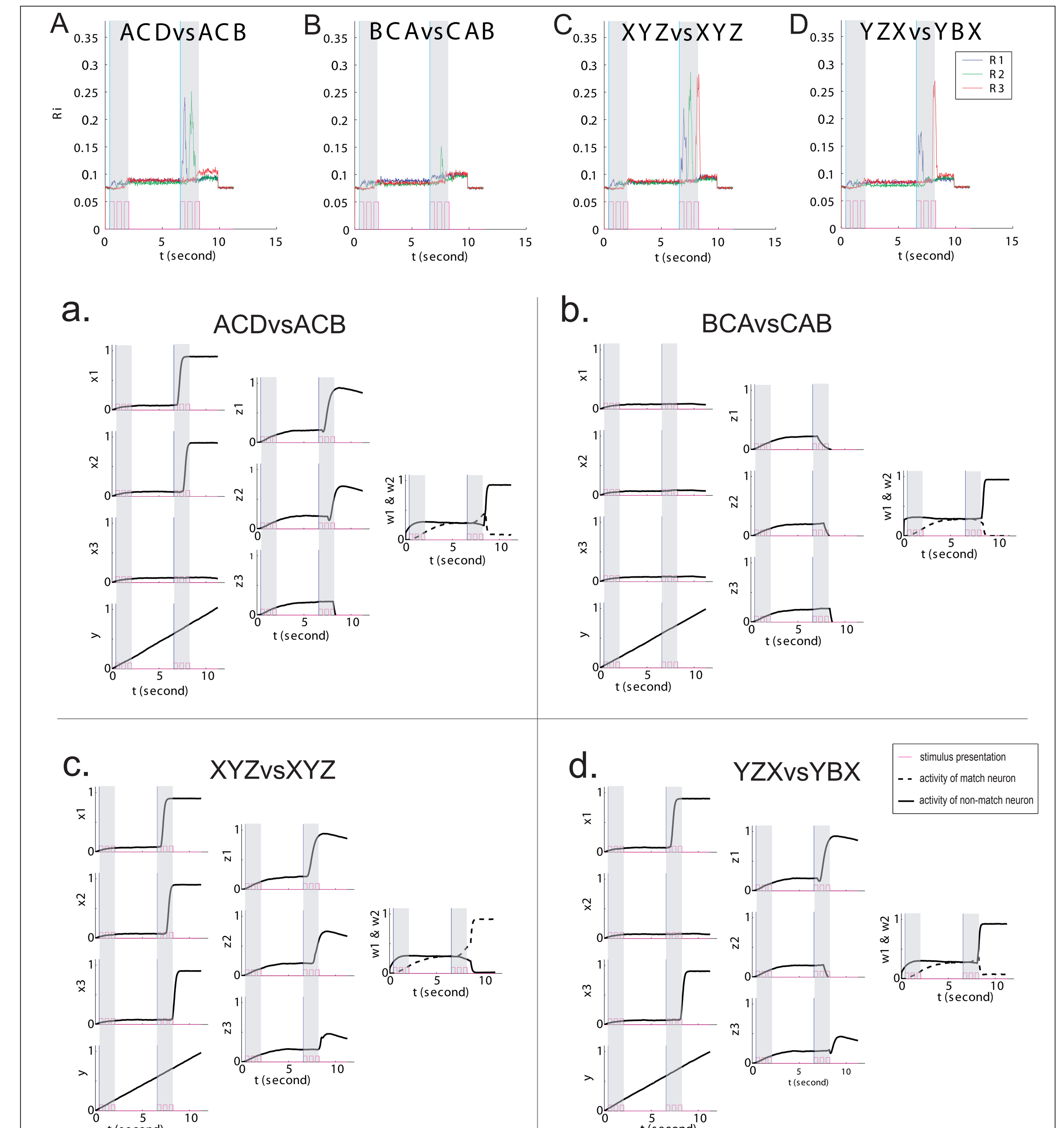


Figure 5. Panels A to D (uppercase letter) show the activities from the response units of the APR model for match and non-match trials. Panel A shows a third-segment mismatch trial. Panel B shows a multi-segment non-match trial. The trials shown in panels A and B have similar tonal-contour segments but in different order. Each individual tonal-contour segment within the trials of panels A and B was used to train the decision-making model. Panel C shows a match trial. Panel D shows a second-segment mismatch trial. The trials shown in panels C and D have similar tonal-contour segments, which, however, are different with the ones in panel A and B. The tonal-contour segments, X,Y and Z, within the trials of panels C and D were not used for the training.

Panels a to d (lowercase letter) show the neural activities of all the neurons of the decision-making model corresponding to the Ri of panels A-D, respectively. The outputs show that the decision-making model does give the correct answer.

Conclusion

The decision making model builds a bridge from perception (auditory pattern recognition) to action (finger movement). The simulated reaction times produced by the decision making model are consistent with the experimental data. The simulated electrical activities of the model neurons qualitatively match those found in recent single-cell recording studies of simple decision-making on monkey. The simulated patterns of neural activities provide insights into the neural interactions from perception to action in the delayed match-to-sample task.

References

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