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# Supplementary Materials for

## Signal dynamics of midbrain dopamine neurons during economic decision-making in monkeys

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**This PDF file includes:**

Figs. S1 to S10

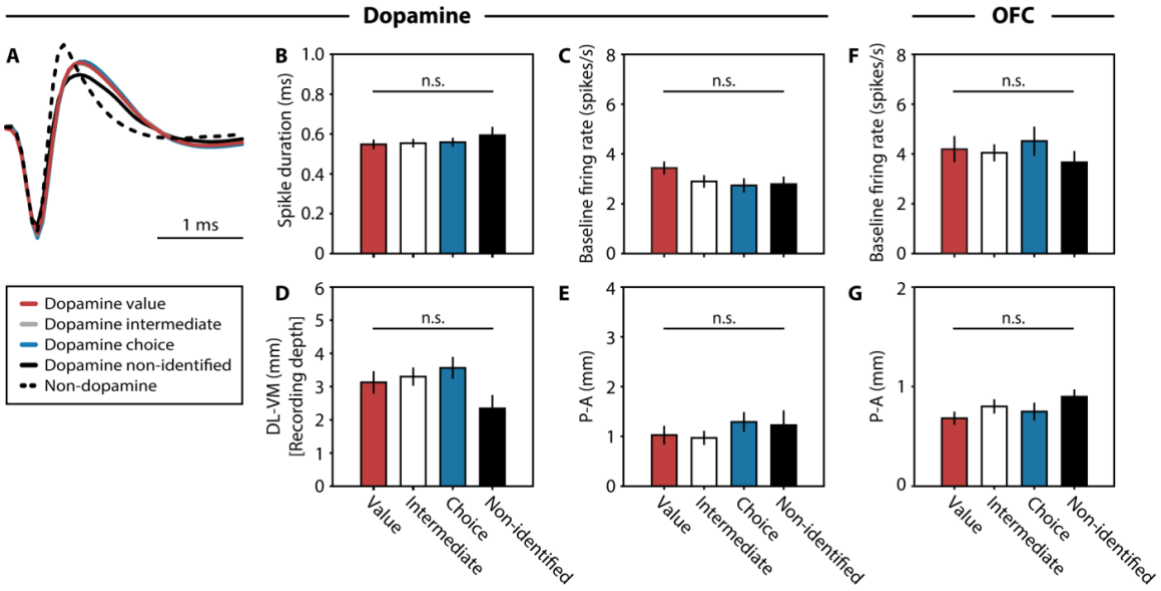


**Fig. S1. Electrophysiological and location differences between neuron groups.** (**A**), Averaged spike shapes of the value-modulated ($N$ = 38) (red), intermediate ($N$ = 52) (gray), choice-modulated ($N$ = 32) (blue) and non-identified dopamine neurons ($N$ = 22) (black), and non-dopamine neurons in the substantia nigra pars reticulata ($N$ = 19) (dotted black). (**B** and **C**), Spike durations (B) and baseline firing rates (C) of the value-modulated (red), intermediate (white), choice-modulated (blue), and non-identified dopamine neurons (black). Error bars indicate SEM. n.s. indicates no significant difference between neuron groups (spike duration, $H$ = 1.38, $P$ = 0.71; baseline firing rate, $H$ = 4.97, $P$ = 0.17; Kruskal-Wallis test). (**D** and **E**), Dorsolateral-ventromedial (D) and posterior-anterior (E) locations of each dopamine neuron group. n.s., no significant difference (dorsolateral-ventromedial, $H$ = 5.98, $P$ = 0.11; posterior-anterior, $H$ = 2.10, $P$ = 0.55; Kruskal-Wallis test). (**F**), Baseline firing rates of the value-modulated ($N$ = 101), intermediate ($N$ = 106), choice-modulated ($N$ = 64), and non-identified OFC neurons ($N$ = 98). n.s., no significant difference ($H$ = 5.19, $P$ = 0.16; Kruskal-Wallis test). (**G**), Posterior-anterior location of each OFC neuron group. n.s., no significant difference ($H$ = 4.49, $P$ = 0.21; Kruskal-Wallis test).

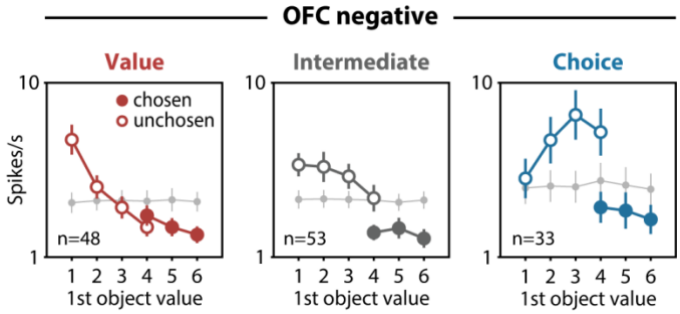


**Fig. S2. OFC neurons that negatively represented the option's value and/or monkey's choice.** Averaged activity magnitudes of value-modulated (*N* = 48) (left), intermediate (*N* = 53) (middle), and choice-modulated OFC neurons (*N* = 33) (right) that negatively represented these signals. Conventions are as Fig. 4D and E. Note that some OFC neurons represented the option's value and/or monkey's choice in both the positive and negative manners for different periods during the presentation of the first object. Thus, the total number of the positive OFC neurons (value-modulated neurons, *N* = 54; intermediate neurons, *N* = 54; choice-modulated neurons, *N* = 34) and the negative OFC neurons (value-modulated neurons, *N* = 48; intermediate neurons, *N* = 53; choice-modulated neurons, *N* = 33) was larger than the number of the identified OFC neurons (value-modulated neurons, *N* = 101; intermediate neurons, *N* = 106; choice-modulated neurons, *N* = 64).

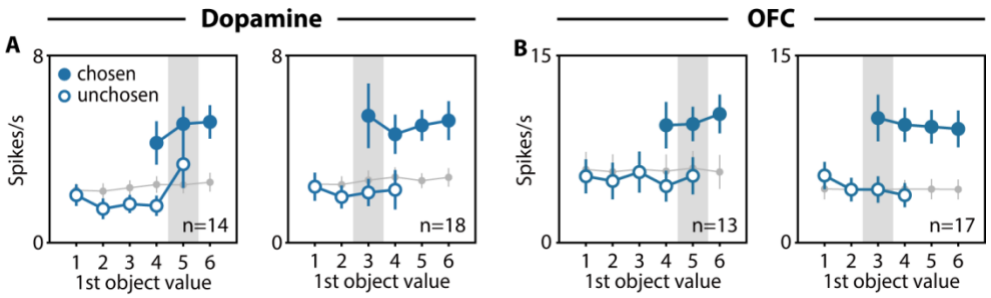


**Fig. S3. Responses of choice-modulated dopamine and OFC neurons to the first objects with value 3 and 5.** (**A** and **B**), Averaged magnitudes of choice-modulated neuron activity shown for dopamine neurons (A) and OFC neurons (B). Left: averaged activity including the responses to the first object with value 5 in chosen and unchosen trials (gray area). Right: averaged activity including the responses to the first object with value 3 in chosen and unchosen trials (gray area). Conventions are as the bottom panels in Fig. 2A-F. It should be noted that there were only a few chosen trials when the first object value was 3, while there were only a few unchosen trials when the first object value was 5. Therefore, only a limited number of choice-modulated neurons of which the recording session fortuitously contained these few trials were able to be used for this analysis. As population, choice-modulated neurons exhibited a stronger activation in chosen trials than in unchosen trials even if the object value was 3 or 5 in both dopamine and OFC neurons. Because of the limited numbers of trials and neurons, a statistically significant difference was observed only in the response to the object with value 3, but not in the response to the object with value 5, for both dopamine and OFC neurons (dopamine neurons: value 3, $N = 18$, $P = 0.034$; value 5, $N = 14$, $P = 0.15$; OFC neurons: value 3, $N = 17$, $P = 1.9 \times 10^{-3}$, value 5, $N = 13$, $P = 0.17$; two- tailed Wilcoxon signed-rank test).

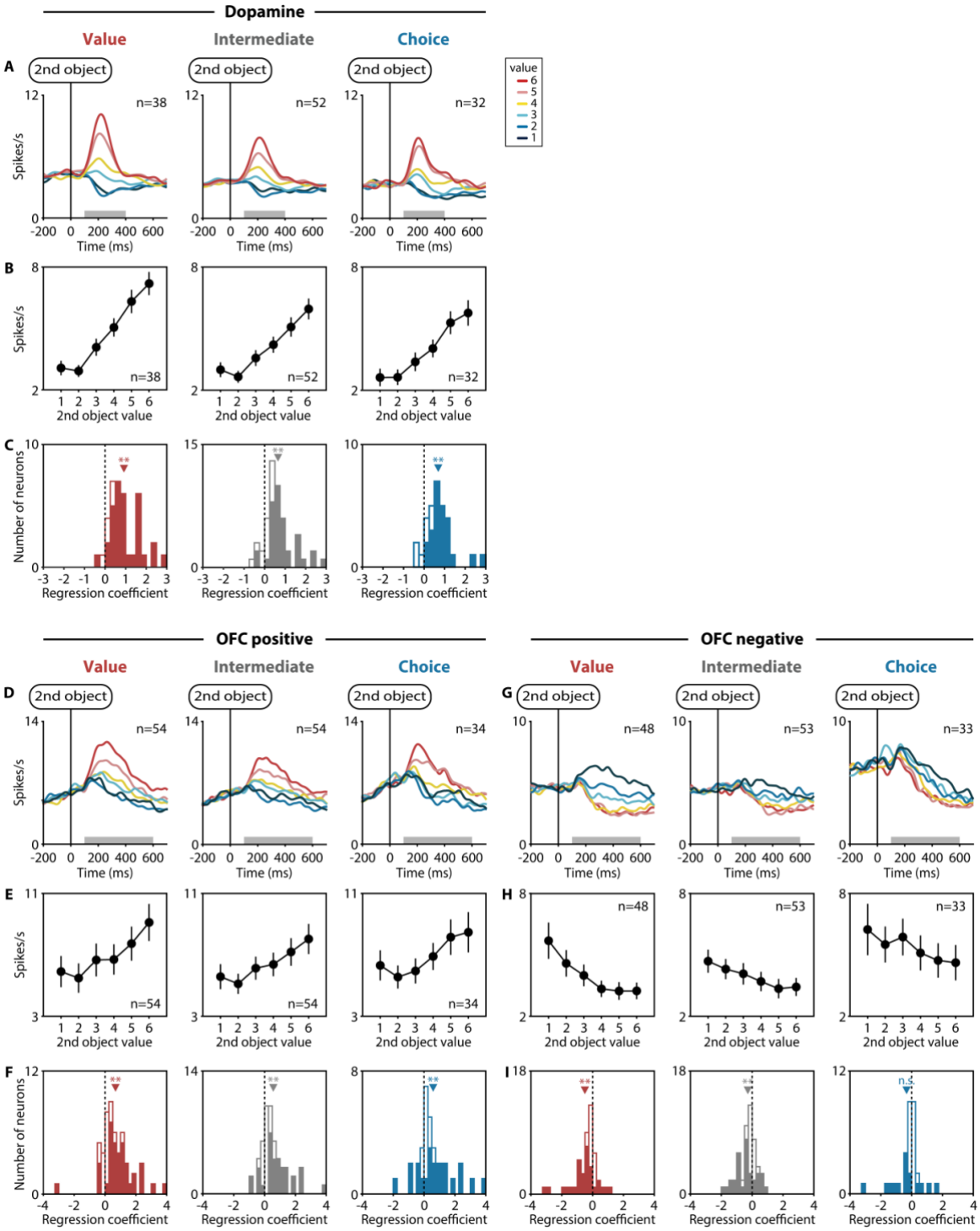


**Fig. S4. Response of each neuron group to the second object.** (**A, D** and **G**), Averaged activity aligned by the onset of the second object in trials in which the monkey did not choose the first object. The activity is shown for value-modulated (left), intermediate (middle), and choice-modulated neurons (right), and shown for dopamine neurons ($N$ = 38, 52, and 32, respectively) (A), OFC neurons positively representing value and/or choice ($N$ = 54, 54, and 34, respectively) (D), and OFC neurons negatively

representing value and/or choice ($N$ = 48, 53, and 33, respectively) (G). The SDFs are shown for each value. Gray horizontal bars indicate the time window to calculate the magnitude of neuronal activity. (**B, E** and **H**), Averaged magnitude of neuronal activity evoked by the second object. Error bars indicate SEM. (**C**, **F**, and **I**), Regression coefficients between the magnitude of neuronal activity evoked by the second object and the second object value. Solid bars indicate neurons with a significant regression coefficient ($P < 0.05$). Arrowheads indicate mean regression coefficients. Double asterisk indicates a significant deviation from 0 ($P < 0.01$, two-tailed Wilcoxon signed-rank test). n.s., no significant deviation from 0 ($P > 0.05$, two-tailed Wilcoxon signed-rank test).

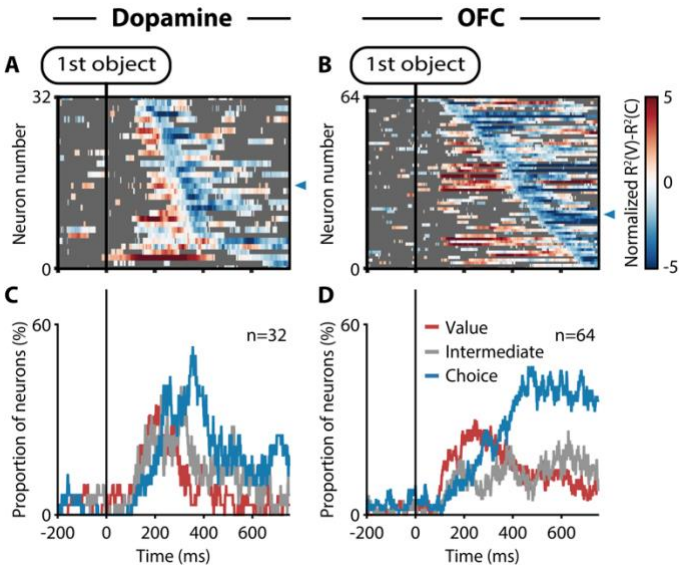


**Fig. S5. Temporal profile of the choice-modulated neurons during economic decision-making.** (**A** and **B**), Temporal profile of the R-square difference between the value and the choice models for each choice-modulated dopamine neuron (*N* = 32) (A) and each choice-modulated OFC neuron (*N* = 64) (B). The OFC data used in this analysis include the 34 and 33 choice-modulated OFC neurons that represented the choice in the positive and negative manners, respectively. However, since three of these neurons represented the choice in both the positive and negative manners for different periods during the presentation of the first object, the total neuron number used for this analysis is 64. Conventions are as Fig. 3C and D. (**C** and **D**), Time-varying proportions of value-modulated, intermediate, and choice-modulated signals of the choice-modulated dopamine neurons (*N* = 32) (C) and the choice-modulated OFC neurons (*N* = 64) (D). Many of these neurons encoded the value-modulated and/or intermediate signals especially before encoding the choice-modulated signal. Conventions are as Fig. 5A and B.

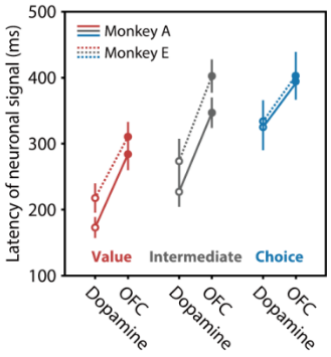


**Fig. S6. Latencies of each dopamine and OFC signals calculated for each monkey.** Red, value-modulated signal; gray, intermediate signal; blue, choice-modulated signal. Solid lines, monkey A; dotted lines, monkey E. We conducted a 2-way ANOVA and examined the effects of 'animal' (monkey A vs. monkey E) and 'recording region' (dopamine neurons vs. OFC neurons) on the latency of each signal. First, the latency of each signal was influenced by 'recording region'. Specifically, the latency of each signal was shorter in dopamine neurons than in OFC neurons, though the effect of 'recording region' was slightly non-significant in the choice-modulated signal (value-modulated signal, $P = 8.4 \times 10^{-4}$; intermediate signal, $P = 1.7 \times 10^{-5}$; choice-modulated signal, $P = 0.052$; 2-way ANOVA). Next, the latency of any signal was not significantly affected by 'animal' (value-modulated signal, $P = 0.24$; intermediate signal, $P = 0.07$; choice-modulated signal, $P = 0.81$; 2-way ANOVA) or the interaction of 'animal' and 'recording region' (value-modulated signal, $P = 0.76$; intermediate signal, $P = 0.87$; choice-modulated signal, $P = 0.995$; 2-way ANOVA). Thus, the tendency of the signal latency, i.e., the latency of each signal was shorter in dopamine neurons than in OFC neurons, was maintained across monkeys.

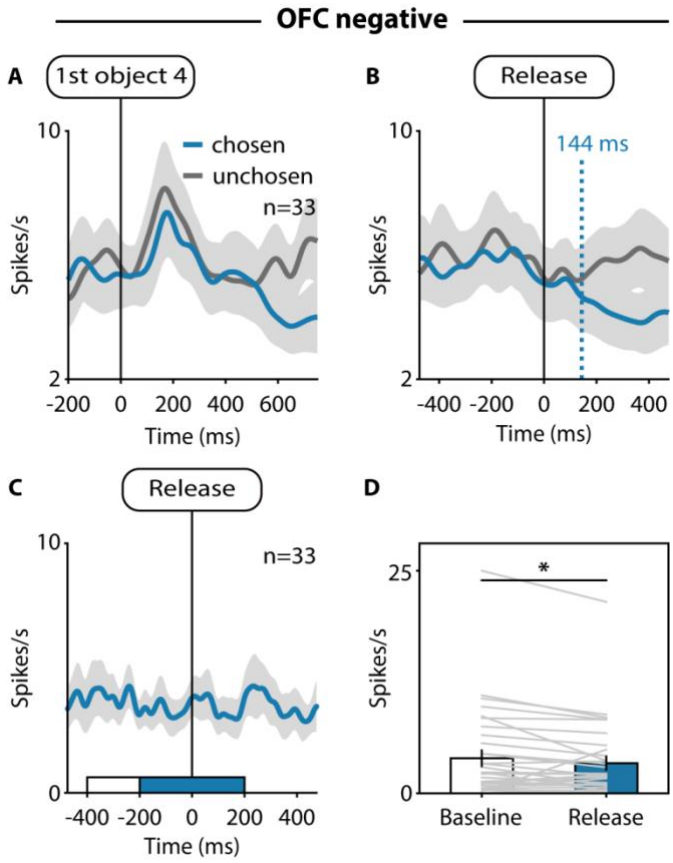


**Fig. S7. Button release-aligned modulation of OFC neurons negatively representing choice in the economic decision-making task and control task.** (**A** and **B**), Averaged SDFs of the choice-modulated OFC neurons that negatively represented the choice ($N$ = 33) aligned at the first object onset (A) and the button release onset (B) shown for chosen (blue) and unchosen trials (gray) under the condition in which the object value was 4. Conventions are as Fig. 6. The choice-modulated signal started later than the onset of the monkey's button release. (**C**), Averaged SDFs of the choice-modulated OFC neurons that negatively represented the choice aligned at the button release onset in the control task. Conventions are as in Fig. 7C and E. (**D**), Comparison between the baseline firing rate and the firing rate around the button release onset in the control task for the choice-modulated OFC neurons that negatively represented the choice. Single asterisk indicates a significant difference between the firing rates ($P$ < 0.05, two-tailed Wilcoxon signed-rank test). Conventions are as in Fig. 7D and F. These OFC neurons showed a weak but significant inhibition around the onset of the button release ($z$ = -2.25, $P$ = 0.024, two-tailed Wilcoxon signed-rank test).

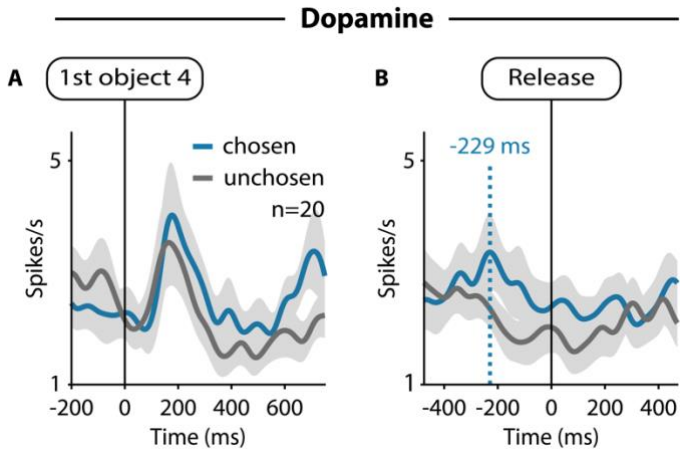


**Fig. S8. Averaged SDFs of the 20 choice-modulated dopamine neurons of which activity was measured using both the economic decision-making task and the control task.** (**A** and **B**), The illustrated data were collected during the decision-making task. Conventions are as Fig. 6. Although these neurons did not show a significant modulation around the onset of the button release as a population during the control task ($z$ = -1.13, $P$ = 0.26, two-tailed Wilcoxon signed-rank test) (Fig. 7C, D), they exhibited a clear excitation aligned by the onset of the button release in the decision-making task (fig. S8B).

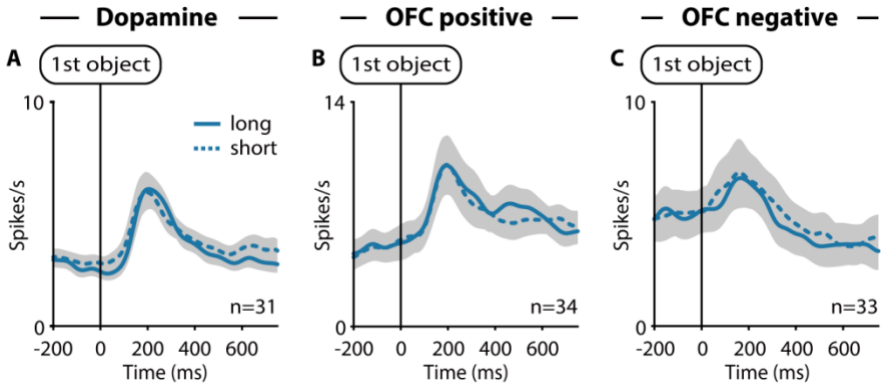


**Fig. S9. Relationship between the latency of the button release and the activity of choice-modulated neurons.** (**A** to **C**), Averaged SDFs of choice-modulated dopamine neurons (*N* = 31) (A), OFC neurons positively representing the choice (*N* = 34) (B), and OFC neurons negatively representing the choice (*N* = 33) (C) in trials with longer (solid curves) and shorter (dotted curves) button release latencies. To calculate the averaged SDFs, we first sorted the button release latencies into longer, middle and shorter ones for each first object value (only for values 4, 5 and 6) and for each neuron. Spike data in trials with the longer and shorter latencies were used to calculate SDFs for each first object value. The SDF averaged across all first object values was regarded as the SDF of each neuron. Then, we averaged the SDFs of all neurons separately for the longer and shorter latencies. Shaded areas around the curves indicate SEM.

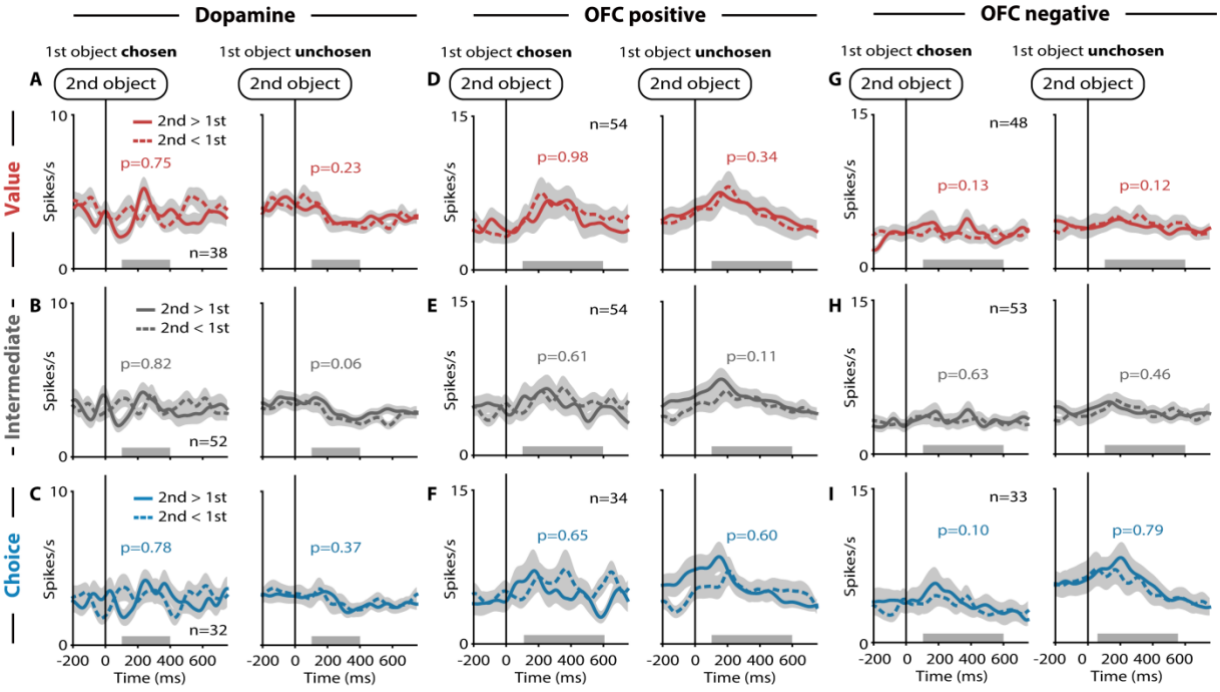


**Fig. S10. Response of each neuron group to the second object of which the value was better or worse than that of the first object.** (**A** to **I**), The averaged activity aligned by the onset of the second object are shown for dopamine neurons (A to C), OFC neurons positively representing value and/or choice (D to F), and OFC neurons negatively representing value and/or choice (G to I), and are shown for value-modulated (red curve), intermediate (gray curve), and choice-modulated (blue curve) neurons. Left column indicates the activity when the monkey chose the first object, while right column indicates the activity when the animal did not choose the first object. Solid curves indicate the activity when the second object value was better than the first object value, while dashed curves indicate the activity when the second object value was worse than the first object value. No significant difference in the activity between the 'better' and 'worse' conditions was observed during the calculation window (gray horizontal bar) ($P > 0.05$, two-tailed Wilcoxon signed-rank test). Shaded areas around the curves indicate SEM.