Neural processes during adolescent risky decision making are associated with conformity to peer influence

Supplementary Materials

Behavioral Driving Simulator Task

Simulated driving environment: The simulated driving worlds were programmed with clear daylight conditions in which all elements (such as pedestrians) were set to minimize the chance of crashes. In study 1, participants were asked to follow a vehicle for correct directions. In study 2, the confederate passenger was asked to provide directions for the driver with the goal of getting to a concert.

Passenger manipulation. The confederate manipulation included three phases: first, when the confederate arrived to the study appointment late, safe and risky confederates gave different excuses to the participant. The safe confederate stated: “Sorry I was a little late getting here. I tend to drive slower, plus I hit every yellow light.” And the risky confederate stated “Sorry I was a little late getting here. Normally I drive way faster, but I hit like every red light.” Second, the participant and confederate were asked to watch two short driving videos (one low risk driving, one high risk driving; in random order) together. After each video, the participant and confederate were asked to rate “how similar is your driving to the driver in the video”, and “how likely would you be to ride with the driver in the video” on ten-point scales. The confederate’s responses to these two questions were consistent with their assigned condition. Participants were asked to complete a five-minute word puzzle before the solo drive in order to provide a control task to the video rating task. Third, during the drive session, the confederates in sample 2 provided mild peer pressure by commenting with risk-accepting or risk-averse norms (e.g., noting high or low speed limits). However, the confederates in sample 1 did not comment on how to drive. We trained the confederates to comment and provide directions at the same points during every drive. Confederates in sample 1 did not give feedback related to driving during the drive session.

Linking neural activity in subclusters of $ROI_{stake\text{-}modulated}$ and driving behavior

Mean activation analyses. Results from main analyses suggested that peer influence type marginally moderated the relationship between stake-modulated neural activation in $ROI_{stake\text{-}modulated}$ (consisting the ACC, bilateral insula, thalamus, and rMFG) and risky driving behavior ($b = .32$, $t(76) = 1.92$, $p = 0.058$), suggesting that the relationship between stake-modulated neural activation and risky driving behavior marginally depended on the type of peer influence. Based on this finding, we conducted exploratory analyses to examine whether subcluster(s) of $ROI_{stake\text{-}modulated}$ was more strongly associated with susceptibility to peer influence during risk taking (Table S1). The results suggested that the ACC cluster was most strongly associated with conformity to risk promoting peers. Peer influence type significantly moderated the relationship between stake-modulated ACC activation during BART and risky driving behavior ($b = -.53$, $t(76) = -4.25$, $p_{uncorrected} < .0001$, $p_{corrected} = .0006$; Table S1, model 1). No significant interaction between stake-modulated neural activation and peer influence type was found for other clusters (AI: Table S1, Model 2; thalamus: Table S1, model 3; rMFG: Table S1, Model 4).

Table S1. Multiple regression model results showing the effects of stake-modulated activation in subclusters of $ROI_{stake\text{-}modulated}$, peer influence type, and their interaction effect on driving behavior (positive relationships mean more risk taking at higher ROI values), controlling for sample wave, scanner ID, and drive order. Risky peer influence was set as the reference level.

	β	SE	t	p
Model 1: ACC (R^2 = .26)				

Intercept	-.75	.88	-.85	.40
ACC activation	.48	.11	4.56	.0006* (corrected) .00002 (uncorrected)
Peer influence type	.09	.22	.40	.69
ACC activation x Peer influence type	-.53	.13	-4.25	.0002* (corrected) .00006 (uncorrected)
Scanner ID	.07	.30	.59	.56
Sample Wave	.17	.30	.59	.56
Drive Order	.39	.20	1.98	.05†
Model 2: AI (R^2 = .07)				
Intercept	.07	1.03	.07	.94
AI activation	.10	.11	.88	.38
Peer influence type	-.04	.30	-.14	.89
AI activation x Peer influence type	-.15	.13	-1.11	.27 (uncorrected) 1 (corrected)
Scanner ID	-.08	.33	-.24	.81
Sample Wave	-.09	.33	-.27	.79
Drive Order	.37	.22	1.65	.10
Model 3: thalamus (R^2 = .13)				
Intercept	-.55	.97	-.56	.57
Thalamus activation	.27	.10	2.68	.01*
Peer influence type	-.12	.25	-.46	.65
Thalamus X Peer influence type	-.23	.13	-1.70	.09 (uncorrected) .93

				(corrected)
Scanner ID	.05	.32	.15	.88
Sample Wave	.15	.32	.45	.65
Drive Order	.35	.22	1.63	.11
Model 4: rMFG (R^2 = .07)				
Intercept	.20	.99	.20	.84
RMFG activation	.02	.09	.26	.80
Peer influence type	-.10	.27	-.39	.70
RMFG X Peer influence type	-.13	.13	-1.04	.30 (uncorrected) 1 (corrected)
Scanner ID	-.09	.33	-.26	.80
Sample Wave	-.10	.32	-.30	.76
Drive Order	.36	.13	-1.04	.30

† $p < .1$, * $p < 0.05$.

PPI analyses. We conducted functional connectivity analyses to examine whether VS and risk processing regions may interact to change each other's influence. Our results showed a significant interaction effect between stake-modulated ROI_{VS} and $ROI_{stake\text{-}modulated}$ functional connectivity and peer influence type on driving behaviors (b = 7.57, t(76) = 2.82, p = .006), with a significant negative simple effect of stake-modulated functional connectivity on risky driving when participants drove with a risky passenger (b = -7.14, t(76) = -3.26, p = .002). We conducted additional exploratory analyses to examine if connectivity between ROI_{VS} and subcluster(s) of $ROI_{stake\text{-}modulated}$ was more strongly associated with driving. No subcluster of $ROI_{stake\text{-}modulated}$ interacted with peer influence type to predict risky driving after controlling for multiple comparison (Table S2).

Table S2. Multiple regression model results showing the effects of stake-modulated functional connectivity between ROI_{VS} and each subcluster of $ROI_{stake\text{-}modulated}$, peer influence type, and their interaction effect on driving behavior (positive relationships mean more risk taking at higher ROI values), controlling for sample wave, scanner ID, and drive order. Risky peer influence was set as the reference level.

	β	SE	t	p
Model 1: ROI_{VS}-ACC connectivity (R^2 = .14)				
Intercept	.77	.94	.81	.42
ROI_{VS}-ACC connectivity	-3.84	1.58	-2.43	.02*
Peer influence type	-.30	.22	-1.37	.18
ROI_{VS}-ACC connectivity x Peer influence type	2.27	1.98	1.15	.25 (uncorrected) 1 (corrected)
Scanner ID	-.28	.32	-.88	.38
Sample Wave	-.21	.31	-.67	.50
Drive Order	.46	1.98	1.15	.25
Model 2: ROI_{VS} - AI connectivity (R^2 = .07)				
Intercept	.40	.95	.42	.68
ROI_{VS} - AI connectivity	6.80	5.40	1.26	.21
Peer influence type	-.21	.22	-.94	.35
ROI_{VS} - AI connectivity x Peer influence type	-9.22	6.67	-1.38	.17 (uncorrected) 1 (corrected)
Scanner ID	-.19	.33	-.58	.57
Sample Wave	-.14	.32	-.45	.66
Drive Order	.40	6.67	-1.38	.17
Model 3: ROI_{VS} -Thalamus connectivity (R^2 = .07)				
Intercept	.53	.98	.54	.59
ROI_{VS} -Thalamus connectivity	-1.12	1.67	-.67	.50

Peer influence type	-.32	.22	-1.41	.16
ROI_{VS} -Thalamus connectivity X Peer influence type	2.41	2.03	1.19	.24 (uncorrected) 1 (corrected)
Scanner ID	-.17	.34	-.51	.61
Sample Wave	-.19	.32	-.59	.56
Drive Order	.38	.23	1.71	.09†
Model 4: ROI_{VS} -rMFG connectivity (R^2 = .11)				
Intercept	.52	.93	.56	.58
ROI_{VS} -rMFG connectivity	-2.21	1.05	-2.11	.04
Peer influence type	-.28	.22	-1.31	.19
ROI_{VS} -rMFG connectivity X Peer influence type	3.30	1.58	2.09	.04 (uncorrected) .40 (corrected)
Scanner ID	-.21	.32	-.65	.52
Sample Wave	-.19	.31	-.60	.55
Drive Order	.42	.22	1.86	.07†

† $p < .1$, * $p < 0.05$.

Findings from the BART Inflate vs. Rest Contrast

BART neuroimaging results. We examined brain activations when participants were inflating the balloons compared to rest during the BART. For the balloon inflation contrast, replicating past results (Schonberg et al., 2012), we found significant neural activation in regions including the VS, supplementary motor area, thalamus, and cerebellum (FDR corrected p < 0.05; Figure S1, Table S3).

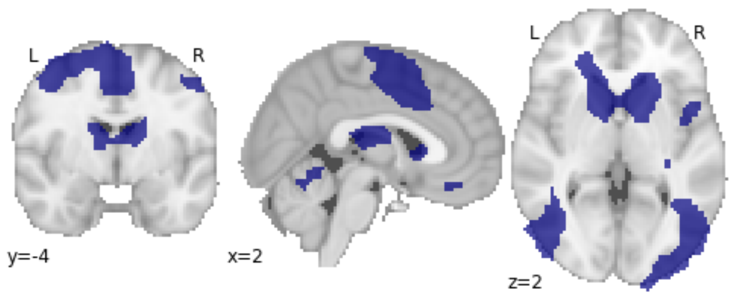

Figure S1. Significant brain activation in BART when participants were inflating the balloons compared to rest (inflate vs. rest contrast; FDR corrected p < .05). The regions include VS, ACC, thalamus, and cerebellum.

Table S3. Mean neural activations associated with the balloon inflation vs. rest contrast in the BART.

	Peak MNI coordinates				
Brain region	*x*	*y*	*z*	*t*	*k*
Positive clusters					
L/R striatum	18.2	22.1	4	6.98	141
L/R thalamus	14.81	-29.5	16	6.10	157
L/R supplementary motor area	1.1	4.9	61	6.37	137
R cerebellum posterior lobe	42.3	-60.4	-38	8.05	1477
L cerebellum posterior lobe	-40.2	-68	-28	6.90	330
Negative clusters					
R occipital lobe	11.4	-91.4	7	-6.04	112

Note. L and R refer to left and right brain hemispheres; x, y, and z refer to MNI coordinates; t refers to the t-score at the local maxima; k refers to the number of voxels in each significant cluster. Whole brain analysis is FWE corrected to $p < 0.05$, $k>25$.

Region of interest (ROI). Two sets of ROIs were included in the analyses for the BART inflate vs. rest contrast. First, given our a-priori interest in examining the role of the VS during risk taking, we constructed a VS mask of two 8-mm radius spheres based on MNI coordinates from previous meta-analysis (ROI_{VS}; peak coordinates for VS were selected; right: x=9, y=9, z=−8; left: x=−9, y=9, z=−8; Postuma & Dagher, 2006; see main manuscript Figure 2a). The second set of ROIs was functionally defined to include clusters with significant neural responses during the balloon inflation vs. rest contrast in the BART ($ROI_{inflate}$; FDR corrected $p < 0.05$, $k>50$; Figure S1). The $ROI_{inflate}$ included the VS, thalamus, rMFG, supplementary motor area, and cerebellum posterior lobe.

Activation analyses. Similar to the activation analyses in the main manuscript, we extracted parameter estimates from ROI_{VS} and $ROI_{inflate}$ for neural activation in the BART inflate vs. rest contrast using the MarsBar toolbox for SPM (Brett et al., 2002). We constructed two ordinary least square (OLS) models to examine the association between individual differences in the levels of neural activation in each participant in the BART task in these regions and their later driving behavior. In particular, our main interest was to examine the interaction between neural responses during BART and the effect of different types of peer influence on risky driving behavior. These models were specified as below:

Risky driving ~ mean ROI activation + peer influence type + mean ROI activation x peer influence type + scanner ID + sample wave + drive order,

where mean ROI activation refers to activation in ROI_{VS} or $ROI_{inflate}$ in the BART inflate vs. rest contrast.

Linking BART Neural responses and driving behavior. First, we investigated whether mean ROI activation during BART risk taking predicted risky driving behavior under different types of peer influence. First, with regard to ROI_{VS}, multiple regression results indicated a significant interaction between peer influence type during the simulated drive and mean ROI_{VS} activity during BART (b = .95, t(76) = 2.41, p = .02; Table S4, Model 1; Figure S2a), suggesting that the relation between ROI_{VS} neural activation and risky driving behavior significantly depend on the type of peer riding with driver. A significant simple effect of safe peer influence and mean ROI_{VS} activation on driving behavior (b = -.80, t(76) = -2.40, p = .02) suggests that when adolescents were driving with safe peers, greater mean ROI_{VS} activation was significantly associated with less risky driving behavior. The simple effect of mean ROI_{VS} activation on driving behavior with risky passengers was not significant (b = .15, t(76) = .59, p = .56).

Second, with regard to $ROI_{inflate}$, multiple regression results indicated no significant interaction between peer influence type during the simulated drive and mean $ROI_{inflate}$ activity during BART (b = .24, t(76) = .64, p = .52, Table S4, Model 2; Figure S2b), suggesting that the relation between mean $ROI_{inflate}$ activation and risky driving behavior did not significantly depend on the type of peer riding with the driver. Further exploratory analyses that separately examined each subcluster of $ROI_{inflate}$ showed no significant findings that passed multiple comparison corrections (Table S5).

Table S4. Multiple regression model results showing the effects of mean ROI activation, peer influence type, and their interaction effect on driving behavior (positive relationships mean more risk taking at higher ROI values), controlling for sample wave, scanner ID, and drive order. Safe peer influence was set as the reference level.

	β	SE	t	p
Model 1: ROI_{VS} (R^2 = .13)				

Intercept	.18	.93	.20	.84
ROI_{VS} activation	-.80	.33	-2.40	.02*
Peer influence type	.11	.23	.50	.62
ROI_{VS} activation x Peer influence type	.95	.39	2.41	.02*
Scanner ID	-.10	.31	-.31	.76
Sample Wave	-.16	.33	-.50	.62
Drive Order	.38	.22	1.74	.09†
Model 2: $ROI_{inflate}$ (R^2 = .07)				
Intercept	.82	1.12	.73	.47
$ROI_{inflate}$ activation	-.46	.34	-1.34	.18
Peer influence type	.13	.30	.45	.66
$ROI_{inflate}$ activation x Peer influence type	.24	.37	.64	.52
Scanner ID	-.15	.33	-.46	.65
Sample Wave	-.42	.42	-1.01	.32
Drive Order	.38	.22	1.72	.09†

† $p < .1$, * $p < 0.05$.

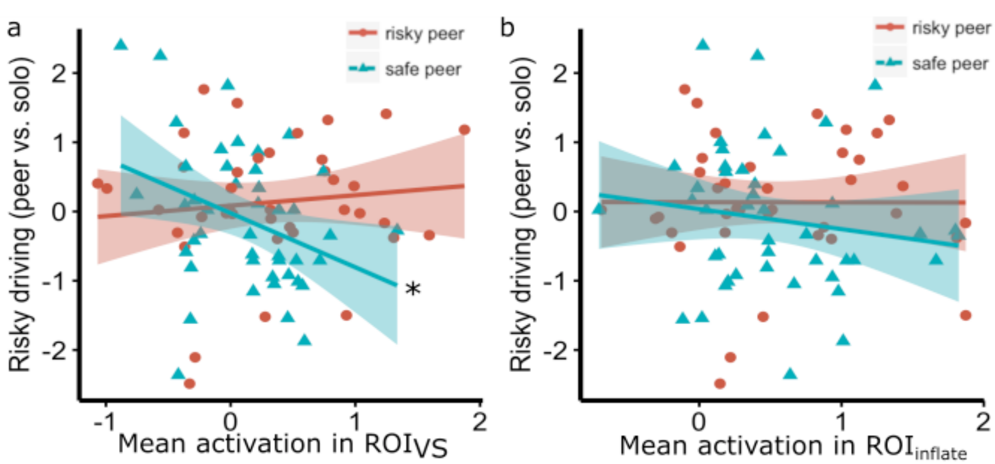

Figure S2. Scatter plot showing the relationship between changes in risky in the driving task and mean BART activation in (a) ROI_{VS} and (b) $ROI_{inflate}$. Peer passenger type significantly moderated the relationship between mean activation in ROI_{VS} in the inflate vs. rest contrast and changes in risky driving in the driving task, with a significant simple effect for the safe peer condition (Fig. S2a). For participants who drove with safe peers, higher ROI_{VS} during BART balloon inflation was associated with safer driving. Peer passenger type did not significantly moderate the relationship between mean activation in $ROI_{inflate}$ and changes in risky driving in the driving task (Fig. S2b). *: simple effects significance p < .05.

Table S5. Multiple regression model results showing the effects of mean activation in subclusters of $ROI_{inflate}$, peer influence type, and their interaction effect on driving behavior (positive relationships mean more risk taking at higher ROI values), controlling for sample wave, scanner ID, and drive order. Safe peer influence was set as the reference level.

	β	SE	t	p
Model 1: striatum (R^2 = .05)				
Intercept	.19	1.01	.18	.85
Striatum activation	-.07	.20	-.37	.72
Peer influence type	.20	.28	.74	.46
Striatum activation x Peer influence type	.08	.24	.33	.75 (uncorrected) 1 (corrected)
Scanner ID	-.14	.33	-.43	.67
Sample Wave	-.14	.36	-.40	.69
Drive Order	.36	.23	1.58	.12
Model 2: thalamus (R^2 = .06)				
Intercept	.17	.97	.18	.86
Thalamus activation	.04	.20	.20	.85
Peer influence type	.36	.28	1.26	.21
Thalamus activation x Peer influence type	-.16	.24	-.65	.52 (uncorrected) 1 (corrected)
Scanner ID	-.15	.33	-.47	.64

Sample Wave	-.18	.34	-.55	.59
Drive Order	.38	.22	1.69	.52
Model 3: supplementary motor area (SMA; R^2 = .06)				
Intercept	.08	.97	.09	.93
SMA activation	.06	.11	.56	.58
Peer influence type	.33	.27	1.20	.24
SMA X Peer influence type	-.07	.16	-.42	.68 (uncorrected) 1 (corrected)
Scanner ID	-.18	.33	-.54	.59
Sample Wave	-.11	.36	-.32	.75
Drive Order	.37	.23	1.64	.11
Model 4: L cerebellum (R^2 = .08)				
Intercept	.64	1.03	.62	.54
L cerebellum activation	-.28	.18	-1.59	.12
Peer influence type	.01	.28	.04	.97
L cerebellum X Peer influence type	.29	.24	1.22	.23 (uncorrected) 1 (corrected)
Scanner ID	-.22	.33	-.67	.51
Sample Wave	-.21	.35	-.60	.55
Drive Order	.30	.23	1.22	.23
Model 4: R cerebellum (R^2 = .08)				
Intercept	.56	1.04	.54	.59
R cerebellum activation	-.32	.20	-1.60	.11
Peer influence type	-.06	.30	-.18	.85
R cerebellum X Peer influence type	.36	.25	1.45	.15 (uncorrected)

				.76 (corrected)
Scanner ID	-.15	.33	-.46	.65
Sample Wave	-.21	.36	-.60	.55
Drive Order	.33	.22	1.47	.15

† $p < .1$, * $p < 0.05$.

Comparing results using "percent time in red" versus "percent failed to stop" as the outcome measure

In the simulated driving task, we measured the extent that individuals took risks while driving in this simulated driving task through 1) the percentage of time spent in the intersections during a red light ("percent time in red"), and 2) the percentage of stops in which participants failed to stop at yellow lights ("percent failed to stop"). "Percent time in red" and "percent failed to stop" were highly correlated ($r(22.7) = .93$, $p < .0001$). In the main manuscript, each of the measures was standardized within the sample before we averaged the two measures into an overall "risky driving score" for simplicity. Here, we provide a comparison of findings in the main manuscript using "percent time in red" and "percent failed to stop" as separate dependent variables (Table S6; Figure S3). These results highlight that using "percent time in red" and "percent failed to stop" as separate outcome measures provide parallel findings to the results in the main manuscript, which uses the composite "risky driving score".

Table S6. Multiple regression model results comparing the effects of mean ROI activation, peer influence type, and their interaction effect on two different driving outcomes ("percent time in red" vs. "percent failed to stop"), controlling for sample wave, scanner ID, and drive order. Risky peer influence was set as the reference level.

Outcome measure	"Percent time in red"				"Percent failed to stop"			
	β	SE	t	p	β	SE	t	p
1. Stake-modulated activation in $\mathbf{ROI_{VS}}$								
Intercept	0.33	0.97	0.34	0.73	0.39	0.96	0.41	0.68
ROI_{VS} activation	0.1	0.11	0.88	0.38	0.11	0.11	0.97	0.34
Peer influence type	-0.22	0.22	-0.97	0.34	-0.31	0.22	-1.41	0.16
ROI_{VS} activation x Peer influence type	-0.04	0.15	-0.26	0.8	-0.03	0.15	-0.22	0.83
Scanner ID	-0.11	0.33	-0.34	0.74	-0.12	0.33	-0.35	0.72
Sample Wave	-0.15	0.32	-0.47	0.64	-0.16	0.32	-0.50	0.62
Drive Order	0.36	0.23	1.57	0.12	0.37	0.23	1.65	0.10
2. Stake-modulated activation in $\mathbf{ROI_{stake\text{-}modulated}}$								
Intercept	-0.43	1.05	-0.41	0.68	-0.21	1.05	-0.2	0.84
$ROI_{stake\text{-}modulated}$ activation	0.27	0.14	1.92	0.06†	0.21	0.14	1.54	0.13
Peer influence type	0.2	0.31	0.64	0.52	0.05	0.31	0.17	0.87
$ROI_{stake\text{-}modulated}$ activation x Peer influence type	-0.35	0.17	-2.04	0.04*	-0.3	0.17	-1.76	0.08†
Scanner ID	0.03	0.34	0.1	0.92	-0.01	0.34	-0.03	0.97

Sample Wave	0.01	0.33	0.04	0.97	-0.03	0.33	-0.09	0.93
Drive Order	0.36	0.22	1.6	0.11	0.38	0.22	1.7	0.09†
3. Stake-modulated activation in ACC								
Intercept	-0.81	0.9	-0.9	0.37	-0.69	0.89	-0.78	0.44
ACC activation	0.49	0.11	4.57	0.000018*	0.47	0.11	4.4	0.000034*
Peer influence type	0.12	0.22	0.55	0.58	0.05	0.22	0.24	0.81
ACC x Peer influence type	-0.52	0.13	-4.11	0.0001*	-0.54	0.13	-4.26	0.000058*
Scanner ID	0.07	0.3	0.23	0.82	0.07	0.3	0.23	0.82
Sample Wave	0.2	0.3	0.65	0.52	0.15	0.3	0.51	0.61
Drive Order	0.38	0.2	1.88	0.06†	0.41	0.2	2.02	0.05†
4. Stake-modulated functional connectivity between ROI_{VS} and $ROI_{stake\text{-}modulated}$								
Intercept	1.13	0.96	1.17	0.24	1.29	0.94	1.37	0.18
ROI_{VS} – $ROI_{stake\text{-}modulated}$ connectivity	-6.77	2.24	-3.02	0.0034*	-7.5	2.19	-3.42	0.0010*
Peer influence type	-0.34	0.22	-1.58	0.12	-0.46	0.21	-2.14	0.04*
ROI_{VS} – $ROI_{stake\text{-}modulated}$ connectivity x Peer influence type	7.11	2.75	2.58	0.01*	8.03	2.69	2.99	0.0038*
Scanner ID	-0.43	0.33	-1.31	0.20	-0.47	0.32	-1.46	0.15
Sample Wave	-0.32	0.32	-1	0.32	-0.35	0.31	-1.12	0.26
Drive Order	0.53	0.22	2.37	0.02*	0.56	0.22	2.59	0.01*

† $p < .1$, * $p < 0.05$.

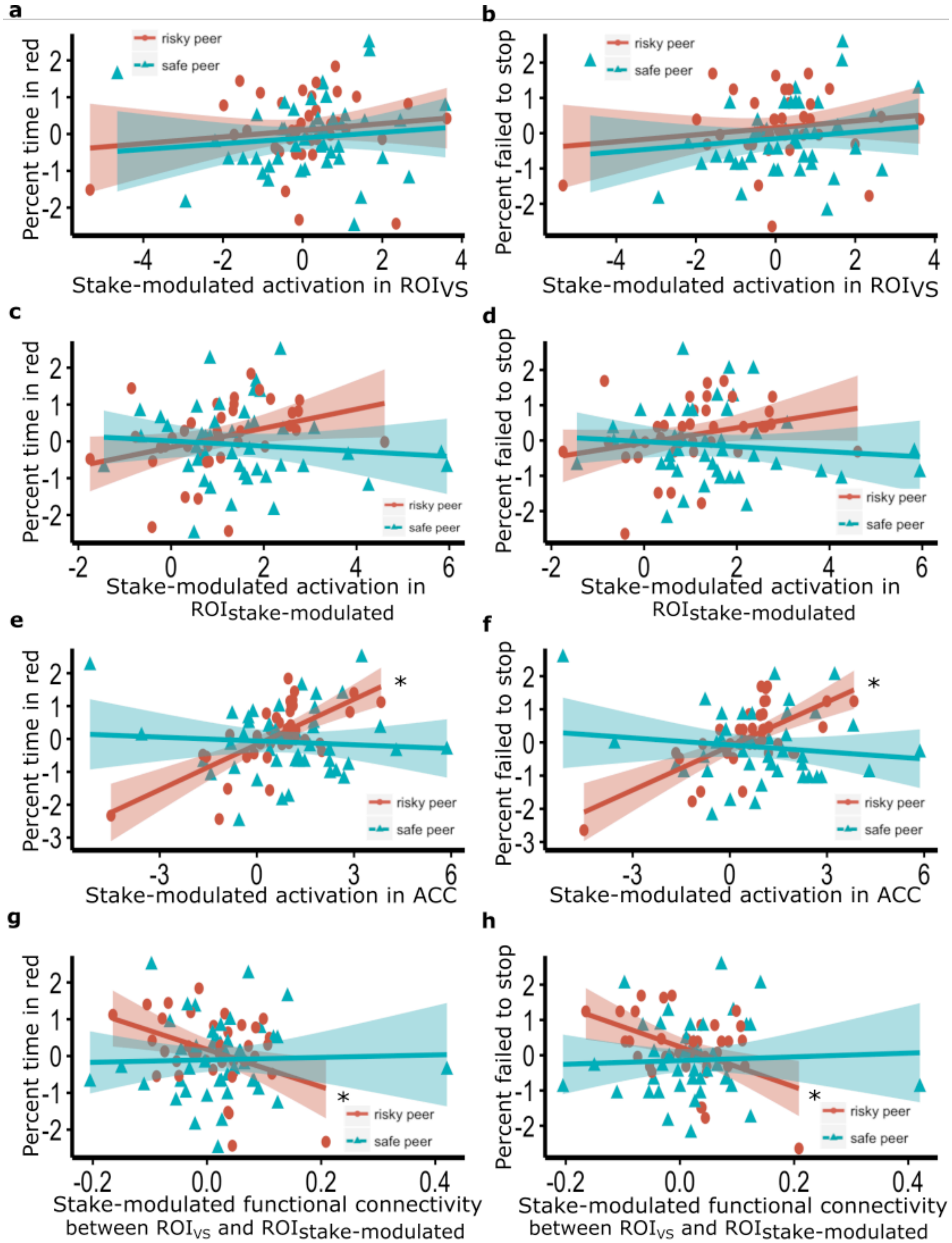

Figure S3. Comparison of main findings using "percent time in red" (a, c, e, g) and "percent failed to stop"(b, d, f, h) as separate dependent variables. P values indicate p values for the interaction between neural responses and passenger type in predicting risky driving ("percent time in red" or "percent failed to stop"). *: simple effects p < .05.

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