# Locus coeruleus-related insula activation supports implicit learning

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**Abstract**

The noradrenergic locus coeruleus and its neuromodulatory cortical projections are critical for adaptive behavior, yet their contributions to implicit learning in novel environments remain incompletely understood, due to challenges in non-invasive assessment. Here, we combined multimodal neuroimaging—including locus-coeruleus-sensitive structural MRI, concurrent pupillometry–fMRI, and PET-derived noradrenergic transporter maps—with repeated behavioral assessments to investigate noradrenergic contributions to implicit learning across younger and older adults (n = 77).

Salient expectation-violating stimuli elicited pupil dilation, indicating enhanced neuromodulation, activated the action-mode network and deactivated the default-mode network. Pupil-linked BOLD responses suggested a functional coupling between the locus coeruleus and action-mode network, further supported by spatial overlap of activation patterns with PET-derived noradrenergic transporter maps. Locus coeruleus MRI-guided functional connectivity analyses demonstrated that locus coeruleus activity is coupled to anterior insula activation, suggesting a noradrenergic role in shifting cortical dynamics toward action-oriented processing.

Behaviorally, participants implicitly learned the statistical task structure over time, as evidenced by reaction time adjustments based on stimulus probabilities. Critically, stronger locus coeruleus integrity, greater task-related anterior insula activation, and more pronounced pupil dilation were associated with enhanced implicit learning, highlighting the behavioral relevance of noradrenergic neuromodulation. Notably, noradrenergic responses and their link to learning were preserved across age groups, suggesting a robust noradrenergic role in supporting adaptive behavior throughout adulthood.

These findings provide novel insights into the neuromodulatory mechanisms underlying learning and cognitive flexibility, emphasizing the pivotal role of locus coeruleus–action-mode network interactions in behavioral adaptation.

*Keywords:* locus coeruleus, neuromodulation, noradrenaline, norepinephrine, MRI, pupillometry, attention, memory, implicit learning, aging

## 1. Introduction

Optimal behavior requires dynamic adaptation to changing environments [1]. On a neurochemical level, unexpected environmental changes transiently increase noradrenaline release from the locus coeruleus, a brainstem nucleus that facilitates attention and learning [2–4]. Specifically, noradrenaline release has long been conceptualized as a neural interrupt signal that promotes rapid behavioral adaptation to new environmental imperatives[5–8]. The momentary processing of salient stimuli is thereby facilitated by a noradrenergic enhancement of neural gain, effectively increasing signal-to-noise ratios in neural circuits[2,9–12]. By contrast, long-term adjustments to salient events are mediated by noradrenergic influences on hippocampal synaptic plasticity[3,13–16].

In a similar vein, more recent accounts propose that the locus coeruleus is activated when predictions about the world are violated. The resulting noradrenaline release helps refine internal model of the world by adjusting the rate of learning in cortical target regions[17–21].

To enable these functions, the locus coeruleus receives critical contextual information about stimulus salience and utility from cortical structures such as the anterior cingulate and insula[2,9]. In primates, these forebrain structures send major direct inputs to the locus coeruleus to recruit noradrenergic neuromodulation and modulate brain-wide processing according to environmental demands[9].

The anterior cingulate and insular cortices have recently been grouped into the action-mode network[22], overlapping with the cingulo-opercular network or ventral attention network[6,23,24]. The action-mode network is closely linked to initiating and maintaining states of heightened arousal and focused attention, as well as the generation and updating of actions based on salient internal or external signals[22,25]. In this context, arousal is defined as a continuum of sensitivity to environmental stimuli[26], tightly regulated by noradrenergic neuromodulation[27–29]. In line with this, it has been proposed that the locus coeruleus modulates or is part of the action-mode network[6,22,30], but direct in vivo evidence remains limited.

Aging dysregulates the noradrenergic system[31–33], possibly due to the age-related accumulation of pathology[34–37]. In accordance with this, converging evidence based on cognitive assessments suggests that age differences in proxies of noradrenergic neuromodulation contribute to late-life impairments in attention[38–40], learning, and memory[41–43]; i.e., in situations when participants were *explicitly* instructed about the cognitive testing. However, the role of the locus coeruleus in how younger and older adults *implicitly* learn to adapt their behavior in new situations remains underexplored.

Here, we investigated the implications of locus coeruleus–cortical network interactions for implicit behavioral adaptation using a multimodal age-comparative approach. To this end, we used a modified conditioned oddball task, previously shown to reliably increase locus coeruleus spiking in non-human primates[44]. In this variant of the oddball task, participants detect infrequent, distinctive stimuli amid a series of repetitive standard stimuli. To further increase recruitment of the locus coeruleus, infrequent oddball stimuli are pre-conditioned by repeatedly pairing them with appetitive or aversive outcomes[40,44–46]. Our participants completed the conditioned oddball task twice on consecutive days. Trial-level behavioral responses from the task allowed us to examine implicit learning within and across sessions. In this context, implicit learning refers to how initially naïve participants pick up the statistical regularities of the originally new but increasingly familiar task environment and optimize their behavior over time (i.e., without explicit instructions).

To overcome challenges in non-invasive assessment posed by the locus coeruleus' small size and location in the brainstem[47–49], we relied on several recent additions to the neuroscience toolkit. In particular, dedicated structural magnetic resonance imaging (MRI) sequences can reveal the locus coeruleus as a cluster of distinct bright (hyperintense) voxels

bordering the fourth ventricle[41,49]. Transgenic animal[50,51] and human post-mortem[52] validation studies suggest this signal may serve as an in-vivo proxy for locus coeruleus integrity. Here, we relied on neuromodulation-sensitive MRI to assess individual differences in locus coeruleus integrity and to reliably localize the small brainstem nucleus in functional analyses. To additionally track locus coeruleus activation patterns, we combined fMRI with concurrent pupillometry, as increasing arousal-related neuromodulatory activity, including in the noradrenergic system, dilates pupils[53–55]. Finally, we compared the observed pupillometry–fMRI activation maps to the brain-wide distribution of noradrenergic and other neuromodulatory transporters[56] to gauge potential dependencies. In sum, younger and older adults completed a conditioned oddball task while we assessed multiple proxies for locus coeruleus structure and function to explore their role in implicit learning.

In a brief synopsis of our findings, salient stimuli reliably dilated younger and older participants' pupils and activated the action-mode network. Pupil-indexed neuromodulation correlated with brainstem and action-mode network activation, and was associated with noradrenergic transporter distribution, suggesting potential links to the locus coeruleus, which we confirmed using functional connectivity analyses. Initially naïve participants implicitly learned the structure of the new task environment and adapted their behavior over time. Behavioral adaptation (i.e., implicit learning) was positively associated with structural and functional locus coeruleus and action-mode network measures. Together, these results suggest that noradrenergic signals support refining internal models of environmental contingencies for behavioral adaptation by modulating attention and memory following salient events. By integrating advanced MRI, pupillometry, and functional connectivity analyses, we reveal critical insights into how neuromodulatory signals dynamically drive behavioral flexibility.

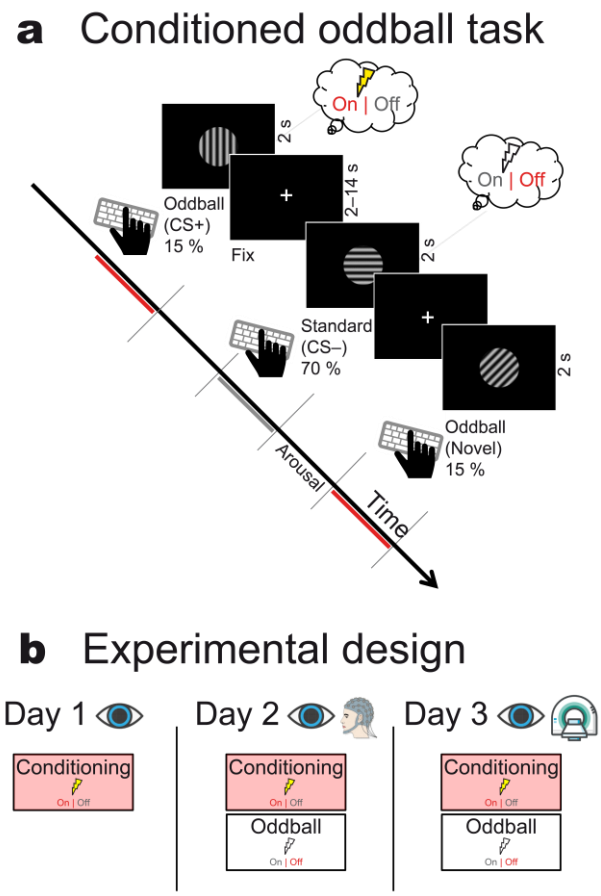


***Figure 1.*** **Overview of the conditioned oddball task (a) and experimental phases (b)**. As part of a three-stimulus oddball task, previously conditioned stimuli (CS+) are presented as infrequent oddball stimuli while non-conditioned perceptually matched control stimuli (CS–) serve as frequent standards. A second oddball category consists of perceptually matched but previously not shown stimuli, hypothesized to elicit a novelty response. (**b**) Fear conditioning sessions are repeated over three consecutive days while collecting eye tracking and EEG data. The conditioned oddball task takes place on Day 2 (pupillometry-EEG) and Day 3 (pupillometry-fMRI). During the oddball tasks, no electrical stimulation is applied.

## 2. Results

*Conditioning reliably increases pupil-indexed neuromodulation across age groups*

To increase recruitment of the locus coeruleus, experimental stimuli that were subsequently shown in the main task were pre-conditioned by repeatedly pairing them with an aversive electrical stimulation (Figure 1,[44]). Robust pupil dilation following presentation of conditioned stimuli (CS) relative to perceptually matched control stimuli (CS–) suggests this procedure enhanced neuromodulatory activation, including in the noradrenergic system[55], across age groups and assessment days (Figure 2a; all $p_{\text{cluster-corr}} \leq 0.002$).

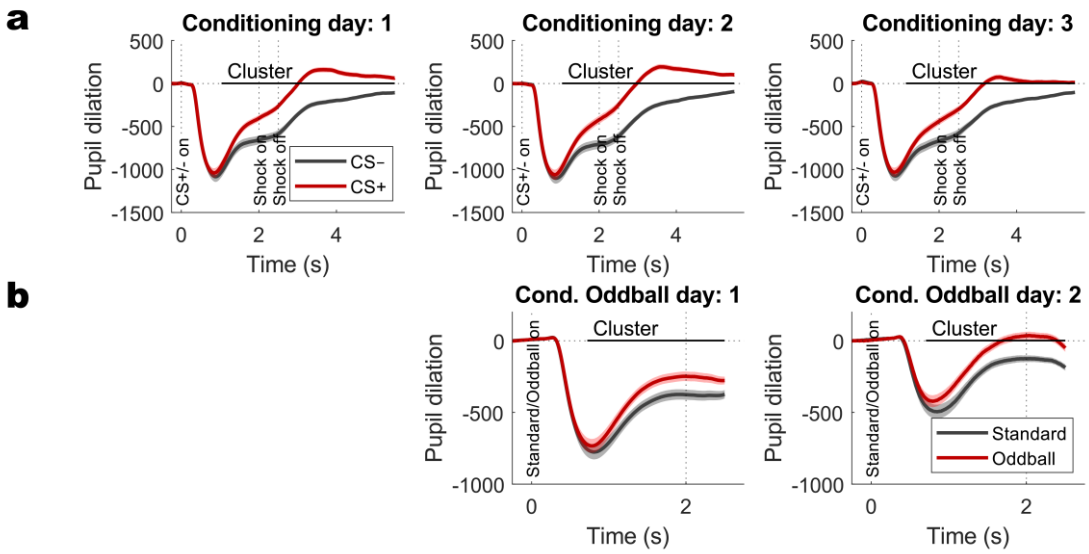


***Figure 2.*** **Stimulus-related pupil responses during fear conditioning (a) and conditioned oddball tasks (b)**. During daily fear conditioning sessions, fear conditioned stimuli (CS+; red) elicit stronger pupil dilation relative to perceptually matched control stimuli (CS–, black), suggesting neuromodulatory activation[53,54]. Note that both stimuli initially elicit comparable pupil constriction due to higher luminance compared to the background (pupil light reflex after stimulus presentation at time 0). (**b**) During subsequent pupillometry-EEG (day 1) and pupillometry-fMRI (day 2) conditioned oddball tasks, oddball presentation (red) is linked to larger pupil dilation relative to perceptually matched control stimuli (standard; black). Differences in pupil light reflexes between oddball acquisitions result from different background luminance in the two laboratories (EEG, MRI). The black horizontal lines indicate the temporal extent of the significant group level cluster, controlling for multiple comparisons, which is comparable across days. Shaded areas represent standard errors of the mean.

*Conditioned oddball stimuli dilate the pupil and activate the action-mode network*

During the subsequent main task, salient stimuli—oddballs that were either pre-conditioned or novel—reliably dilated participants' pupils ($p_{\text{cluster-corr}} \leq 0.002$) and activated the action-mode network relative to perceptually matched control stimuli (standards [CS–]; Figures 2b and 3).

Action-mode network recruitment encompassed the bilateral anterior insula ($T = 11.81$, $p_{\text{FWE-corr}} < 0.001$ MNI: 30, 22, 10), middle cingulate gyrus ($T = 8.95$, $p_{\text{FWE}} < 0.001$ MNI: 3.5, 7.5, 31.5), thalamus ($T = 7$, $p_{\text{FWE}} < 0.001$ MNI: 12, –20, 12) and cerebellum ($T = 7.67$, $p_{\text{FWE}} < 0.001$ MNI: 30, –50, –24;[22,25]). In addition, salient stimuli elicited prominent dorsal attention-network activation (bilateral superior parietal lobule; $T = 13.8$, $p_{\text{FWE-corr}} < 0.001$ MNI: 42, –38, 50;[6,25]) and default-mode network *de*activation (e.g., bilateral frontal pole, $T = -11.64$, $p_{\text{FWE}} < 0.001$ MNI: –4, 68, 4;[22]). The un/thresholded whole-brain contrast maps are available at osf.io/4t5hj.

Together, this suggests task-related neuromodulatory activation, as indicated by pupil dilation, as well as activation of the action-mode network, reflecting major cortical in- and output regions of the noradrenergic system[6,9,57]. This may indicate that in response to salient expectation-violating stimuli, there is a transition from default-mode to action-mode network activation, likely facilitated by noradrenergic neuromodulation, which supports coping with changing task demands[5,17,22].

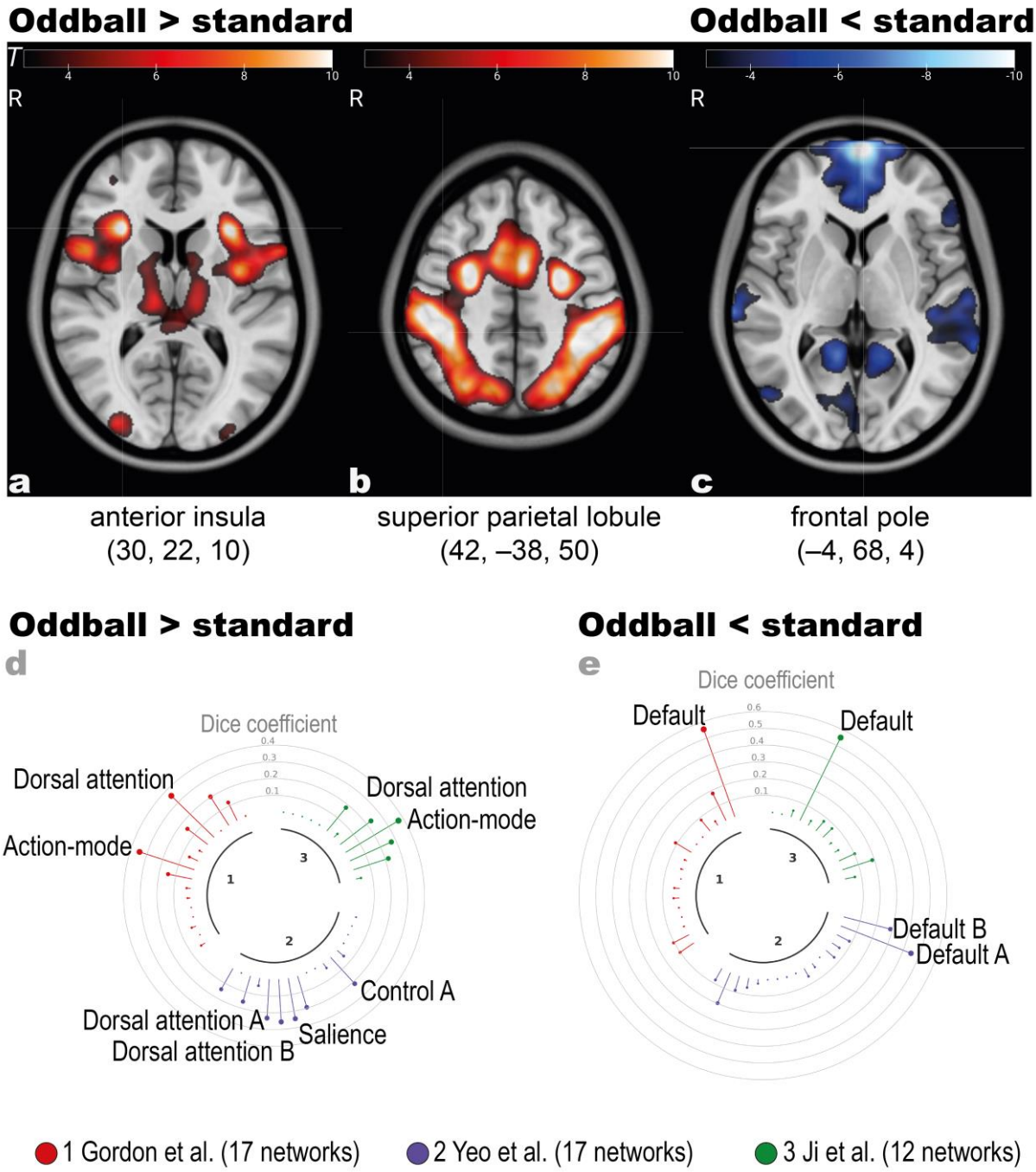


***Figure 3.*** **Salient oddball stimuli elicit action-mode network (a) and dorsal attention network activation (b) and deactivate the default mode network (c).** For visualization, group contrast maps (oddballs vs standards) are thresholded at $T = 3$, main text results report family-wise error corrected statistics. Contrast maps are available at: osf.io/4t5hj. Numbers below the labeled regions indicate MNI XYZ-coordinates. **(d-e)** Overlap of group-level activation **(d)** and deactivation **(e)** maps with three published functional network atlases[23,58,59], quantified as Dice coefficients. Only networks with a significant overlap based on permutation tests [24] and Dice coefficients > 0.2 are labeled. Note that the *Action-mode network* has previously been termed *Cingulo-opercular network*[22] and the *Salience network* is also termed *Ventral attention network*[24].

*Pupil-indexed neuromodulation is associated with action-mode network and brainstem activation*

By integrating pupil time series into the fMRI analyses, we directly probe the relationship between the detected cortical activation patterns and markers of neuromodulation. This approach allowed us to test which brain regions' activity correlated with moment-to-moment pupil fluctuations, which are likely driven by release of neuromodulatory neurotransmitters[53–55].

Supporting an association between noradrenergic neuromodulation and action-mode activation, network hubs such as bilateral anterior insula ($T = 7.31$, $p_{\text{FWE-corr}} < 0.001$ MNI: –32, 20, –8), middle cingulate cortex ($T = 5.55$, $p_{\text{FWE-corr}} < 0.001$ MNI: –4 –0 44), and thalamus ($T = 7.88$, $p_{\text{FWE-corr}} < 0.001$ MNI: 14 –12 10) scaled their activity with pupil size (Figure 4). The un/thresholded whole-brain contrast maps are available at osf.io/4t5hj.These findings corroborate recent observations—linking human intracranial insula recordings with pupil dynamics[30]—and extend them to a functional network level.

Importantly, these pupil–fMRI analyses also revealed a bilateral brainstem–midbrain cluster ($T = 7.27$, $p_{\text{FWE-corr}} < 0.001$ MNI: –4 –30 –14), overlapping with key noradrenergic, serotonergic, and dopaminergic nuclei, in accordance with recent work in rodents[55,60,61] and primates[62–64].

In sum, we found that neuromodulatory and action-mode network regions activated when pupils dilated, suggesting neuromodulatory drive of network transitions.

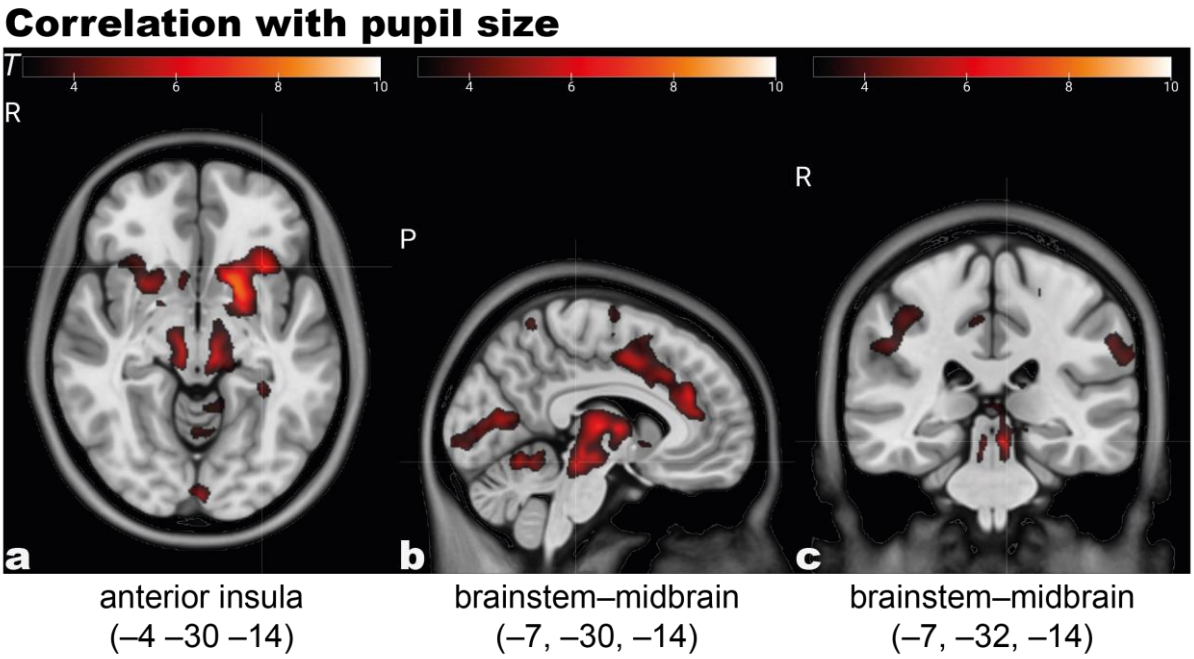


***Figure 4.*** **Moment-to-moment changes in pupil size correlate with action-mode network (a) and neuromodulatory brainstem–midbrain activation (b–c).** For visualization, group contrast maps are thresholded at $T = 3$, main text results report family-wise error corrected statistics. Contrast maps are available at: osf.io/4t5hj. Numbers below the labeled regions indicate MNI XYZ-coordinates.

*Noradrenergic transporter distribution overlaps with pupil-linked BOLD activation patterns*

If indeed the observed activation pattern is supported by noradrenergic release in the cortex, one would expect overlapping spatial distributions with the noradrenergic system. To test this, we leveraged public PET-derived maps of the cortical and subcortical distribution of the noradrenergic transporter[56,65–69]. We then assessed the voxel-wise association of noradrenergic transporter expression and pupil-linked BOLD activation. We detected a robust correlation (Hesse et al. map: $r = 0.189$; $p_{\text{permutation-corr}} < 0.001$), that we replicated using an

alternative noradrenergic transporter map (Ding et al. map: $r = 0.161$; $p_{\text{permutation-corr}} < 0.001$; Figure 5). This suggests that those parts of the brain that activated when pupils dilated overlapped with those housing noradrenergic receptors.

To further contextualize these results, we computed two negative control analyses. Specifically, we linked two brain-wide $GABA_A$ receptor distribution maps[70,71] to our pupil-linked BOLD maps, which we assumed to show no or even a negative association[72]. In line with this, we found that $GABA_A$ receptor expression showed a non-significant negative relation with the pupil–fMRI pattern (Nørgaard et al map: $r = -0.028$; $p_{\text{permutation-corr}} = 0.063$; Dukart et al. map: $r = -0.045$; $p_{\text{permutation-corr}} = 0.056$; Figure 5).

Finally, given that large parts of the brainstem–midbrain, overlapping with noradrenergic, but also serotonergic and dopaminergic nuclei, activated when pupils dilated, we ran two additional analyses to determine whether similar effects extended to other neuromodulatory systems. Both serotonergic (Beliveau et al. map: $r = 0.229$; $p_{\text{permutation-corr}} < 0.001$;[73]) and dopaminergic (Sasaki et al. map: $r = 0.241$; $p_{\text{permutation-corr}} < 0.001$;[74]) transporter expression showed a comparable spatial correspondence with the pupil–fMRI activation pattern. While the cortical innervation of dopaminergic, serotonergic and noradrenergic nuclei is partially overlapping, there are also considerable differences between neuromodulatory systems[3]. To test if the expression pattern of noradrenergic transporters explains unique variance in the observed pupil-linked BOLD maps over and above the other neuromodulatory systems, we estimated multiple regression analyses. Specifically, we compared a base model (including serotonergic and dopaminergic transporter expression as predictors) to a full model additionally including a predictor for the noradrenergic transporter (Table 1). Importantly, we found the full model substantially outperformed the base model, suggesting a unique association of noradrenergic transporter expression and pupil-linked BOLD activation ($\Delta\chi^2(df = 1) = 42909.5$; $p_{\text{permutation-corr}} < 0.001$).

**Table 1:** Multiple regression predicting pupil-linked BOLD activation based on neuromodulatory transporter maps

| Predictor | Estimate | Standard error | *t*-value | *p* |
|---|---|---|---|---|
| NAT | 0.18997 | 0.0009112 | 208.48 | <0.001 |
| 5HTT | 0.084247 | 0.00087668 | 96.098 | <0.001 |
| DAT | 0.20462 | 0.00081556 | 250.89 | <0.001 |

*Note*: NAT, 5HTT, DAT refer to PET-derived noradrenergic, serotonergic and dopaminergic transporter expression maps. To obtain a single noradrenergic predictor, the Hesse et al. and Ding et al. maps were averaged.

Taken together, these analyses suggest that key ascending arousal-promoting systems, including noradrenergic neuromodulation, contribute to the observed pupil-linked subcortical and action-mode network activation.

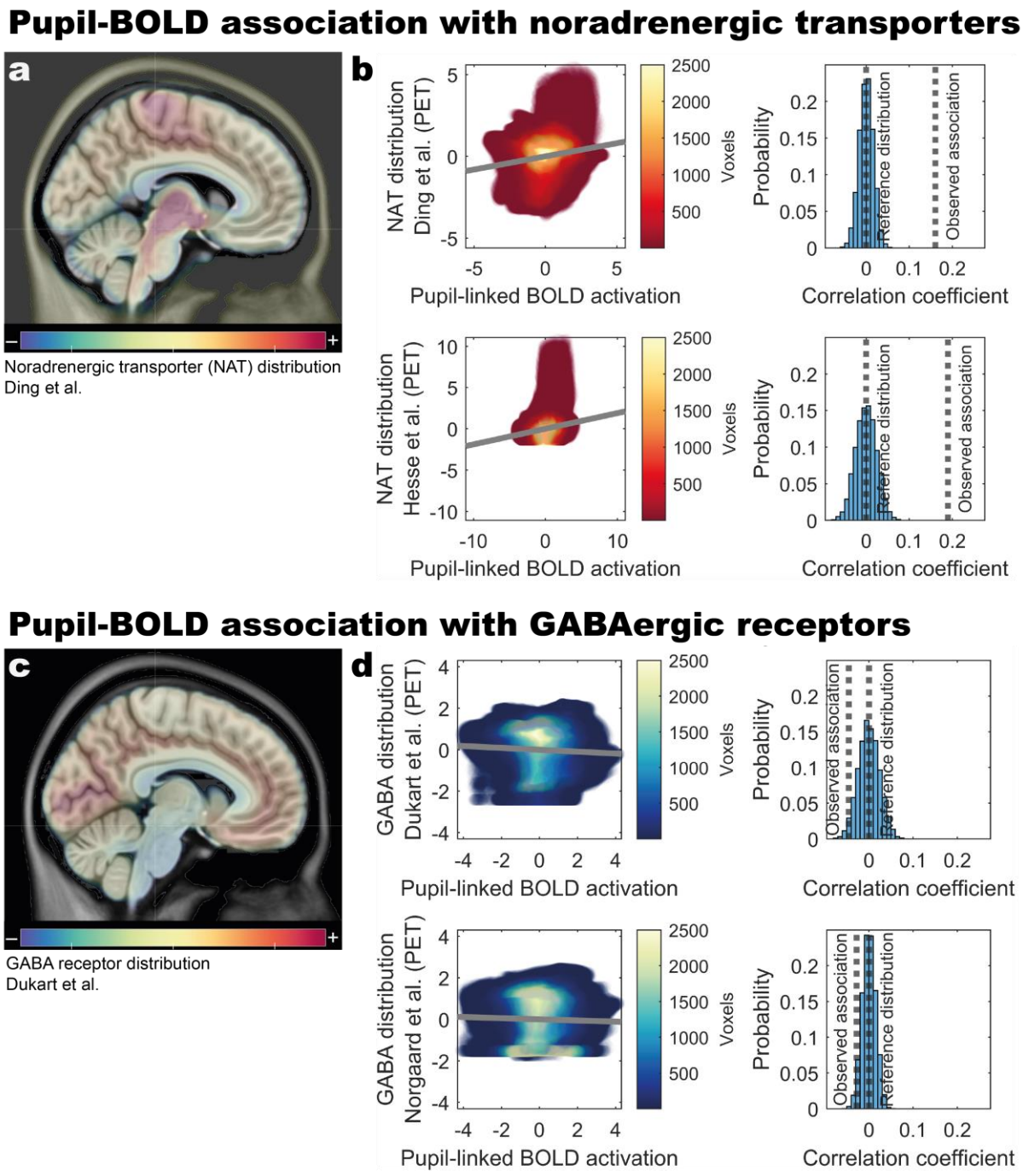


***Figure 5.*** **Voxel-wise association of pupil-linked BOLD activation patterns with PET-derived maps of noradrenergic transporter (a–b) and GABAergic receptor (c–d) distribution**. (**a**) Relative distribution of noradrenergic transporters based on[69]. (**b**) Brain regions activating when pupils dilate overlap with noradrenergic transporter distribution based on two alternative PET maps. (c) Relative distribution of $GABA_A$ receptors based on[70]. (**d**) Brain regions activating when pupils dilate show no systematic overlap with GABAergic receptor distribution based on two alternative PET maps. Observed correlation coefficients are tested against a reference distribution obtained using phase-randomization permutation.

*Locus coeruleus is functionally connected to action-mode network hubs*

So far, our analyses suggest that pupil dilation, likely reflecting neuromodulatory drive, is associated with brainstem and action-mode-network activations. Moreover, the

activated regions closely overlap with noradrenergic receptor distributions as derived from PET atlases. These observations prompted us to test if locus coeruleus and action-mode network activation were directly connected.

Using dedicated neuromodulation-sensitive MRI[49], we estimated person-level proxies for locus coeruleus integrity as well as a group image that visualizes the spatial location of the locus coeruleus adjacent to the fourth ventricle (Figure 6 and osf.io/4t5hj). Notably, the locus coeruleus-related hyperintensity was adequately captured by a previously generated high-confidence mask of this structure ([75]; available at: https://osf.io/sf2ky/).

After this validation step, we used the derived coordinates overlapping with the masked region as seed region for trial-level whole-brain functional connectivity analyses, probing which region's activity co-fluctuated with the locus coeruleus during the conditioned oddball task[76,77]. A bilateral anterior insula ($T = 8.93$, $p_{\text{FWE-corr}} < 0.001$ MNI: –38 12 –10; Figure 6) and thalamus ($T = 6.79$, $p_{\text{FWE-corr}} < 0.001$ MNI: –6.5 –22.5 –2.5) cluster survived correction for multiple comparisons, in addition to a broad cerebellar and pontine activation. The un/thresholded whole-brain contrast maps are available at osf.io/4t5hj. These results point to a co-fluctuation of activity in the locus coeruleus and key action-mode network hubs, in line with known direct anatomical projections[9], as well as our pupil–fMRI and noradrenergic transporter findings.

However, the functional connectivity analyses do not speak to the directionality of this association (brainstem→action-mode network vs. action-mode network→brainstem). Thus, we ran a separate set of analyses, using the TR-level BOLD timeseries of the locus coeruleus and anterior insula (i.e., on a sample level, averaged over voxels). We submitted these to a cross-correlation analysis, which measures the temporal relationship between two signals by quantifying how one variable aligns with shifts in another over time[78], allowing us to assess the temporal precedence of brainstem vs. action-mode network activation. First, we observed a strong coinciding activation (mean cross-correlation coefficient at lag zero: 0.363; $T =$ 11.892), replicating our functional connectivity findings, that stood out above the general association of the two signals (mean cross-correlation coefficient across all lags: 0.217). Note that to better judge the temporal relation of activations, we removed this overall background association by demeaning before group-level cluster-statistics (Figure 6).

Adding to our connectivity analyses, we found that anterior insula activations preceded and predicted subsequent locus coeruleus activations by up to four seconds (mean cross-correlation coefficient at lag –4 s: 0.264; $T = 4.69$; at lag –2 s: 0.255; $T = 2.896$; cluster permutation test: $T_{\text{sum}} = 22.103$; $p_{\text{cluster-corr}} \leq 0.002$; cluster including lags: (–4)–(+2) s). We also observed that preceding locus coeruleus activity was followed by action mode network activation two seconds later (mean cross-correlation coefficient at lag +2 s: 0.25; $T = 2.626$), suggesting a potentially slightly later recurrent connection (brainstem↔action-mode network; contrast of cross-correlation coefficient at lags [–4 to –2; anterior insula leading] vs [+2 to +4; locus coeruleus]: $T = 2.421$; $p = 0.018$). While these analyses do not allow for causal interpretations, they indicate that anterior insula activity may recruit noradrenergic neuromodulation to facilitate subsequent action-mode network activation[5,6]. Taken together, we observed that brainstem activation was functionally connected with action-mode network activity and that this crosstalk may be initiated by the anterior insula, potentially helping participants to efficiently respond to unexpected stimuli[2].

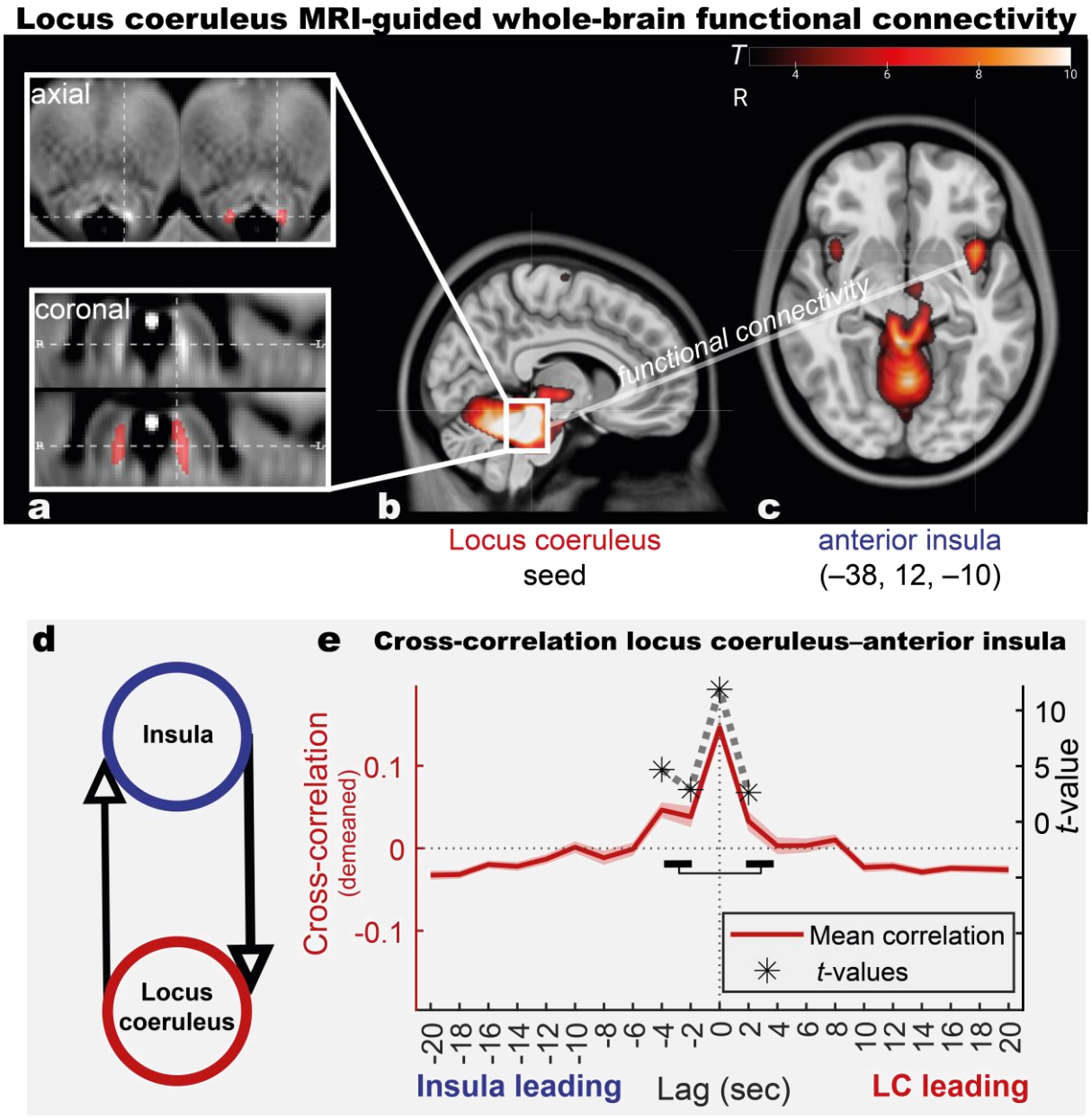


***Figure 6.*** **Locus coeruleus MRI (a) guides whole-brain functional connectivity analyses (b–c), revealing brainstem activation is coupled to and precedes action-mode network activity (d–e).** (**a**) Neuromodulation-sensitive MRI reveals locus coeruleus-related hyperintensity bordering the fourth ventricle that is accurately captured by a high-confidence volume of interest (red;[75]). (**b**) Using this region as seed for whole-brain task-based functional connectivity shows locus coeruleus–anterior insula co-fluctuations. (**d–e**) Cross-correlations replicate the locus coeruleus–anterior insula association and suggest this is initiated by the anterior insula, showing a temporal precedence of up to 4 s (contrast of lags [(–4)–(–2)] vs [(+2)–(+4)]).

*Locus coeruleus and action-mode network support implicit learning of task structure*

To investigate the implications of locus coeruleus–action-mode network interactions during the conditioned oddball task, we analyzed behavioral data. As participants showed high overall accuracy (group mean >0.95), our analyses focused on reaction time dynamics. Participants entered the task without prior knowledge of its statistical structure, yet mean reaction times systematically varied with trial likelihood across the fMRI session (Figure 7a;

$F = 173.83$; $p < 0.001$; mean reaction times per condition: stay-standard: –0.437±0.021, switch-to standard: 0.173±0.031, stay-oddball: 0.442±0.043, switch-to oddball: 0.602±0.040; note that all reaction times are expressed in *Z*-values after log-transformation and within-person standardization). This pattern suggests that participants prioritized responding quickly to frequent trial types at the cost of slower responses to rare events. Supporting this, a strong negative association of the reaction times for stay-standard and switch-to-oddball conditions indicates a performance trade-off between these categories (Figure 7b; $r = –0.795$; $p < 0.001$). We thus assumed that participants implicitly learned the statistical structure of the novel task environment and adapted their behavior, which implies that this reaction time pattern should emerge over the course of the experiment. Combining behavioral data from both repetitions of the conditioned oddball task, we observed that early in the experiment, responses were generally slow and did not differentiate between frequent and rare trials (Figure 7c). However, as the experiment progressed, reaction times to common stimuli became faster, while rare oddballs elicited increasingly slower responses. Accordingly, we found that the difference in reaction times between switch-to-oddball and stay-standard categories increased with time, suggesting implicit learning (Figure 7d; correlation of reaction-time difference and time bin on a group level: $r = 0.509$; $p = 0.003$). This learning pattern detected on a group level was also evident within participants (dependent samples *t*-test of within-participant time-bin beta parameters against zero: $T = 3.194$, $p = 0.002$; mean beta parameter: 0.0097±0.00035; Figure S1). Collectively, these results indicate that participants, initially unfamiliar with the task, gradually internalized its structure and adjusted their behavior accordingly.

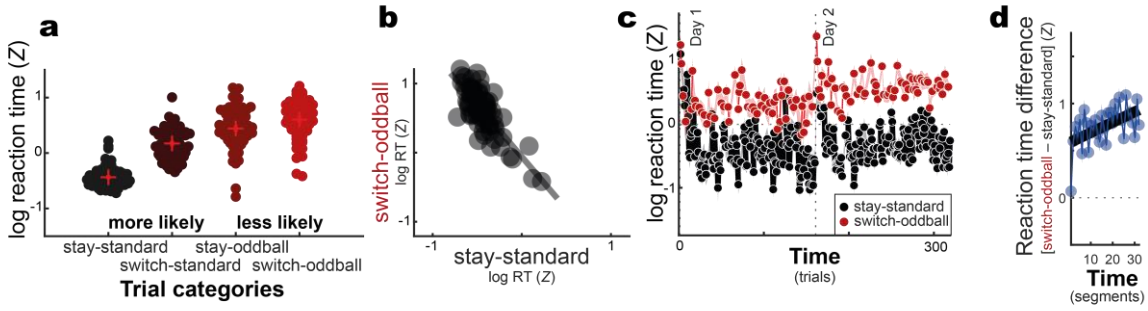


***Figure 7*. Participant focus their behavior on more likely trial categories (a) at the expense of less likely categories (b). This bias emerges across the course of the experiments (c) indicating implicit learning of the task structure (d).** Day 1 indicates the pupillometry-EEG assessment, while day 2 indicates the pupillometry-fMRI oddball assessment. (**a–b**) show day 2 data. (**c–d**) include data of both days.

Finally, we combined imaging and behavioral data to probe if individual differences in markers of the noradrenergic system and its cortical target regions explained implicit learning performance. Specifically, we combined dedicated structural locus coeruleus imaging (Figure 6a and Figure 8a left), task-related pupil dilation (cf. Figure 2b) and locus coeruleus-related anterior insula activation (cf. Figure 3a) in a multivariate partial least-squares correlation with condition-wise reaction times (stay-standard; switch-to standard; stay-oddball; switch-to oddball; Figure 7 and Figure 8a right). We identified one reliable latent component ($r = 0.488$; $p_{\text{permutation-corrected}} = 0.001$). Participants with stronger task-related anterior insula activation (loading onto latent variable: 0.752; bootstrap ratio: 3.402 [interpreted analogous to *Z*-values]), higher locus coeruleus integrity (loading: 0.491; bootstrap ratio: 2.306) and task-related pupil dilation (loading: 0.44; bootstrap ratio: 1.873; trend level association) showed more pronounced differentiation in reaction times between frequent and rare stimuli (cf. Figure 8b). In particular, these participants tended to show quicker responses for frequent trial categories (loadings; stay-standard: –0.468; switch-to-standard: –0.396) at the expense of

slower responses for infrequent trial categories (loadings; stay-oddball: 0.364, switch-to-oddball: 0.701)—recapitulating the implicit-learning pattern we have identified in behavioral analyses (Figure 7c). Post-hoc age group comparisons revealed that younger and older adults showed comparable latent behavioral ($T = -1.36$; $p = 0.179$) and neural scores ($T = -0.209$; $p = 0.835$) and that the latent association did not differ across groups ($Z = 1.111$; $p = 0.133$).

As a sensitivity analysis, we replicated partial least squares-correlation findings using a simpler analytical strategy ($r = 0.466$; $p < 0.001$; by averaging over standardized neural indicators (i.e., insula BOLD activity, locus coeruleus integrity, and pupil dilation, see PLSC analyses) and correlating this composite score with the difference in reaction times to oddball and standard stimuli).

In summary, participants adapted their responses over time to reflect the statistical regularities of the experimental task, demonstrating implicit learning. This implicit learning pattern was stronger expressed in those participants with higher insula activation, higher structural locus coeruleus integrity, and a stronger pupil response to salient stimuli. Together those findings collectively support a role of the locus coeruleus-noradrenergic system in guiding attention and learning to adapt behavior in novel environments[3,6,41].

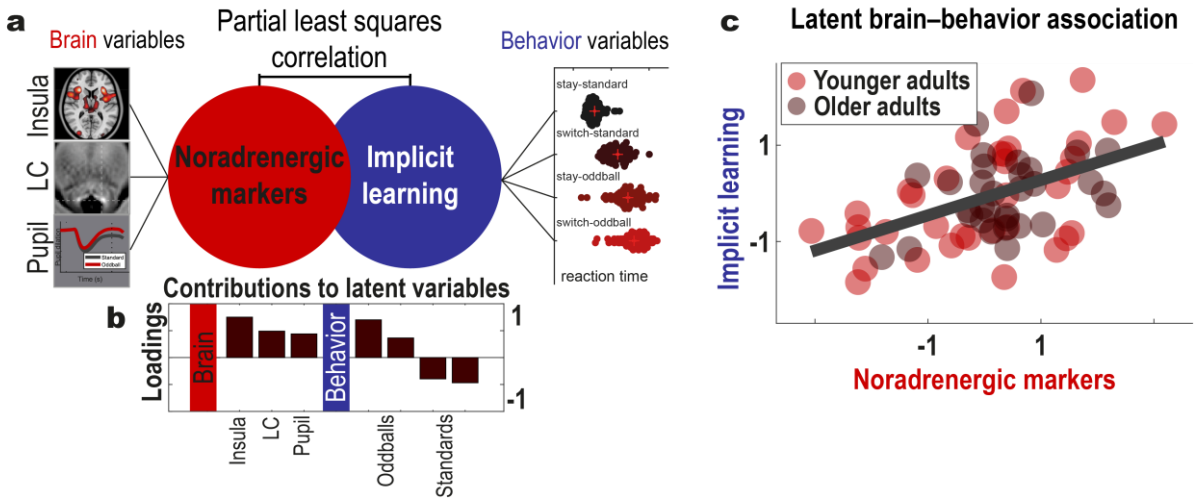


***Figure 8.*** **Individual differences in noradrenergic markers (insula BOLD activity, locus coeruleus integrity, pupil dilation) are associated with implicit learning.** (**a**) Multivariate partial least squares correlation links noradrenergic markers to reaction times for frequent and infrequent trial categories (standards, oddballs, respectively), which reflect that participants implicitly learned the statistical regularities of the task. (**b**) Noradrenergic markers positively contribute to the latent brain variable (e.g., the more activation, the higher scores). On a behavioral level, quicker reaction times for frequent trial categories at the expense of slower reaction times for rare categories are linked to higher latent behavioral scores. (**c**) Participants with higher values in markers of the noradrenergic system demonstrate more implicit learning, a pattern that is comparable across age groups.

## 3. Discussion

This study investigated the role of the locus coeruleus and its cortical targets in how younger and older participants adapt their behavior in dynamic environments with novel observations. We took advantage of repeated assessments of an experimental task shown to modulate noradrenergic activity in primates[44] and a dedicated multimodal imaging protocol to identify neuromodulatory contributions to implicit learning.

We found that salient expectation-violating stimuli dilated participants' pupils, indicating heightened neuromodulatory activity, and triggered a shift from default-mode to action-mode network activation. Combining pupil and BOLD data, we observed that neuromodulatory brainstem–midbrain as well as action-mode network regions scaled their

activity with pupil size. This suggests an interplay between the noradrenergic system and the action-mode network, which we confirmed using PET-derived transporter maps and locus coeruleus-centered functional connectivity analyses. Behavioral data showed that participants implicitly learned the statistical structure of the novel task environment and focused their behavior on more prevalent trial categories, resulting in quicker responses at the expense of slower responses to rare oddballs. Linking brain and behavior, we found that this implicit learning pattern was more pronounced in participants with higher levels of markers associated with the noradrenergic system and its cortical targets. Taken together, this study suggests noradrenergic neuromodulation may upregulate the action-mode network to facilitate (implicit) learning for behavioral adaptation.

*Fear conditioned stimuli evoke robust neuromodulatory responses*

To increase recruitment of the locus coeruleus, a subset of our experimental stimuli was pre-conditioned before the main task by repeatedly pairing them with an aversive outcome[40,44–46]. Conditioned stimuli (CS+) elicited greater pupil dilation than perceptually matched control stimuli (CS–), suggesting increased neuromodulatory drive. Moreover, these effects remained stable across age groups and assessment days, highlighting the robustness of the conditioned response. Our findings are in line with earlier work in rodents demonstrating increased locus coeruleus spiking[79] and noradrenergic axonal activation[45] during conditioning, assumed to support fear learning.

*Noradrenergic neuromodulatory activation is coupled with the action-mode network*

Building on this, during the conditioned oddball task, salient stimuli dilated participants' pupils and activated the action-mode network, including the anterior insula, middle cingulate cortex, thalamus, and cerebellum. This aligns with prior findings implicating the brain's action-mode of function with states of externally focused attention, heightened arousal, and the processing of action-relevant bottom up signals[22,25]. Importantly, these activations were accompanied by default-mode network deactivation, suggesting a functional transition from introspective to externally oriented processing[6]. This is in line with the proposed antagonism of the default-mode and action-mode networks[22] and the more general noradrenergic role in facilitating dynamic reorganizations of target neural networks (also termed network reset[5]).

Combined analyses of pupil and BOLD time series revealed that moment-to-moment fluctuations in pupil size systematically co-varied with activation in the action-mode network (anterior insula, middle cingulate cortex, thalamus). This supports previous intracranial work in humans linking anterior insula activations to variations in pupil size[30] and extends them to a network level. In addition, a brainstem–midbrain cluster encompassing the locus coeruleus and other neuromodulatory nuclei activated when pupils dilated, in line with recent animal research[55,60–62], suggesting that pupil dilation reflects broad neuromodulatory engagement across cortical and subcortical regions[63,64].

An analysis of the spatial overlap between publicly available PET-derived noradrenergic transporter maps and pupil-linked BOLD activation further underscores a role for noradrenergic neuromodulation in regulating these activation patterns[56,65–69]. We found a robust positive correlation, replicating across independent transporter maps, suggesting that brain regions with increased activity during pupil dilation overlap with areas rich in noradrenergic transporters. Negative control analyses with GABAergic receptor maps[70,71] showed no such association, further strengthening the specificity of the association between pupil size, locus coeruleus and action-mode network activation. In line with the broad brainstem–midbrain activation, also serotonergic[73] and dopaminergic[74] transporter maps were positively coupled with the pupil-linked BOLD pattern[63,64]. Crucially, however, noradrenergic

transporter expression explained unique variance in pupil-linked BOLD activation over and above the other neuromodulatory systems.

To more precisely map locus coeruleus activation to its cortical targets, we employed functional connectivity analyses guided by dedicated neuromodulation-sensitive MRI[75]. These analyses revealed that locus coeruleus activity co-fluctuated with action-mode network hubs, particularly the anterior insula and thalamus, consistent with established direct projections in primates[9]. Cross-correlation analyses further elucidated the temporal dynamics of this relationship, suggesting that the anterior insula may recruit locus coeruleus activation up to four seconds later. This finding together with evidence of a recurrent connection support the notion that the insula-initiated recruitment of noradrenergic signaling may facilitate a cortical shift toward an action-oriented state, optimizing adaptive responses to environmental changes[5,6,22]. In this circuit, the anterior insula likely provides crucial contextual signals without which the locus coeruleus would be blind to salient events that require gain-modulation[2]. Our findings are in broad agreement with a recent rodent study in which direct stimulation of the cingulate cortex, another action-mode network hub region, elicited pupil dilation through locus coeruleus activation, suggesting top-down recruitment of brainstem neuromodulation[80]. However, we cannot yet rule out the possibility that differences in the shape of subcortical and cortical hemodynamic responses may contribute to the observed effects, though previous findings do not point in this direction[81].

Notably, beyond the action-mode network, also the salience network includes hub regions in the anterior insula and cingulate cortex[82], and in some atlases networks with these names are overlapping[24]. Similar to the action-mode network, salience network activity has been linked to ascending neuromodulatory systems, including noradrenaline[83]. While our study cannot conclusively disentangle the spatially adjacent and functionally linked networks, the more posterior cingulate and more dorsal anterior insula activation favors an action-mode network involvement ([22,82], see Figure 3).

*Locus coeruleus and action-mode network together support implicit learning*

Finally, we examined behavioral adaptations over the course of the experiments. Participants, initially unfamiliar with the task structure, gradually optimized their reaction times to reflect stimulus probabilities, indicating implicit learning. Optimized reaction times may arise from preparatory movement initiation, resulting in quicker responses for expected stimuli, but slower responses for unexpected stimuli. Crucially, individuals with greater MRI-indexed locus coeruleus integrity, stronger task-related anterior insula activation, and more pronounced pupil dilation showed greater differentiation in reaction times between frequent and infrequent stimuli. This suggests that the locus coeruleus and its cortical targets play a key role in learning and adapting to novel environments, matching previous findings from rodents demonstrating that noradrenergic activity is causal for task execution *and* optimization[84]. In addition, our observations are in line with a recent study in humans relating low MRI-indexed locus coeruleus integrity to diminished practice effects[85]. These result moreover support and extend earlier work using *explicit* cognitive assessments to link noradrenergic markers to attention[38,40], learning, and memory[41,43].

Post-mortem research identified the locus coeruleus as one of the starting points of Alzheimer's-related tau accumulation[36], which may dysregulate noradrenergic activity with increasing age[31,34] and impair late-life cognition[13,33]. Here we found that a latent measure reflecting locus coeruleus integrity as well as pupil dilation and insula activation to salient stimuli did not differ between younger and older adults. This may indicate that externally-driven noradrenergic responses may be comparatively less impaired in aging[38,86]. In addition, we found that this noradrenergic latent variable similarly explained implicit learning across age groups, highlighting its behavioral relevance over the adult lifespan.

*Conclusions*

By combining neuromodulation-sensitive MRI, concurrent pupillometry–fMRI, and PET-derived neuromodulatory transporter maps, our study suggests the noradrenergic locus coeruleus may contribute to a transition from default-mode to action-mode network activation. This mechanism may support adapting behavior to novel environments, reinforcing the importance of neuromodulatory systems in attention, learning and memory.

## 4. Material and methods

*Study design*

Data were collected as part of a larger project investigating neural and cognitive correlates of age-related differences in the noradrenergic system (for details, see[38]). Participants attended three consecutive days of lab-based testing, with the conditioned oddball task administered on the second and third days (Figure 1). On the second day, concurrent pupillometry and electroencephalography (EEG) data were recorded during task performance, while third-day assessments incorporated MRI and pupillometry measurements. To enhance the salience of oddball stimuli, each assessment day included a preceding fear conditioning session, during which the oddball stimuli were repeatedly paired with aversive electrical stimulation. The institutional review board of the German Psychological Association approved the study protocol.

*Participants*

The final sample included 39 younger adults (YAs; mean age ± standard deviation: 25.23 ± 3.23 years; range: 20.17–31 years) and 38 older adults (OAs; mean age: 70.61 ± 2.71 years; range: 65.50–75.92 years), all of whom were male. Two younger adults were excluded from the study after the first assessment day due to low-quality pupil data. Six participants (three per age group) did not participate in the fMRI part of the study (n = 4) or had incomplete eye tracking data (n = 2), leaving a sample of n = 71 for fMRI–pupillometry analyses. All participants were healthy, right-handed, MRI-compatible, fluent German speakers with normal or corrected-to-normal vision, for further characteristics, see[38]. All participants provided written informed consent and were reimbursed for their participation. Exclusion criteria included the use of centrally active drugs, particularly medications affecting the noradrenergic system (e.g., beta-blockers).

*Experimental procedures and stimuli*

*Fear conditioning*

Participants underwent fear conditioning on each testing day to increase the salience of experimental stimuli and their likelihood of eliciting locus coeruleus activation [40,44–46]. During this phase, a sinusoidal luminance pattern (Gabor patch; CS+) with either horizontal or vertical orientation (0° or 90°) was paired with an aversive electrical shock (US) on 80% of trials. A perceptually matched control stimulus (CS–) with the alternate orientation (vertical or horizontal) was never paired with the shock. Stimulus orientation–reinforcement pairings remained consistent for each participant across days and were counterbalanced within age groups (younger adults [YA]: 21:18; older adults [OA]: 20:18).

Each conditioning session comprised 40 trials, with 20 presentations each of CS+ and CS– in pseudorandomized order across assessment days. Trials began with a one-second fixation cross, followed by a two-second visual stimulus (CS+ or CS–). Shocks were delivered for 0.5 seconds immediately after CS+ offset via a bipolar current stimulator (DS5; Digitimer) connected to a ring electrode affixed to participant's left or right index finger. Hand assignment was counterbalanced within age groups (YA: 19:20; OA: 19:19). Each trial concluded with a six-second inter-trial interval, allowing pupil responses to return to baseline.

Participants selected an individually calibrated stimulation intensity deemed unpleasant but not painful before each session[38]. Throughout all conditioning sessions, pupil dilation and gaze position were recorded, and external distractions were minimized.

A procedural error occurred for one older participant, resulting in a reversal of stimulus orientation–shock assignment between the first and second assessment days. This error reduced the likelihood of detecting differences between conditions (CS+/CS–; i.e.,

worked against our hypothesis), but the participant's data were retained for analysis to maintain a larger sample size.

*Conditioned oddball task*

On the second and third assessment days (EEG–pupillometry and fMRI–pupillometry, respectively), participants completed a modified version of a conditioned oddball task previously shown to increase locus coeruleus activity[44].

Specifically, on each trial participants viewed a Gabor patch in one of three possible orientations (horizontal, diagonal, vertical; [0°, 45°, 90°]). Two of these orientations (0°, 90°) were extensively familiarized during preceding fear conditioning (see above) and other tasks within the larger project (see[38]), whereas the third orientation (45°) benefited from relative novelty, hypothesized to enhance neuromodulatory activity[87].

During the conditioned oddball task, one of the stimulus orientations was presented frequently (standard trials; 0° or 90°), while the two other orientations were rarely presented (oddballs). In total, the task consisted of 160 trials presented in pseudorandomized order that differed over assessment days, with the standard, non-conditioned stimulus (CS–) appearing on 70% of trials (112 trials), while the two oddball stimuli (CS+ and the novel 45° orientation) appeared less frequently, each comprising 15% of trials (24 each).

Gabor patches (0°, 45°, and 90° orientation) were displayed for two seconds followed by an inter-trial interval ranging from 2–12 seconds (mean 3.625 seconds; skewed distribution generated with OptSeq2, http://surfer.nmr.mgh.harvard.edu/optseq/).

During Gabor patch presentation, participants were instructed to respond as quickly and accurately as possible by pressing a button corresponding to the orientation of each stimulus using the hand not used for fear conditioning (see above). Accuracy and reaction times were recorded for each trial.

*Physiological data recording and preprocessing*

*Eye tracking*

During all experiments, participants' pupil dilation was measured as an indirect marker of central neuromodulatory activity[53–55] alongside gaze position, using a video-based infrared eye tracker (SR Research EyeLink 1000). On the second day of assessments (during EEG), the desktop mount configuration was used, while on the third day (during fMRI), the long-range mount was employed. The systems operated in a monocular configuration with a spatial resolution of up to 0.25° and a sampling rate of 1000 Hz.

To minimize head movements, participants were seated with their forehead and chin stabilized at a fixed distance of 53.5 cm from the display during the second day. For the MRI session (third day), the eye tracker was positioned within the scanner bore, and data were collected via a mirror affixed to the head coil, which redirected participants' view to the stimulus display.

Participants were instructed to maintain central fixation throughout the experiments. Before each experiment, the eye tracker was (re)calibrated using a standard 5-point grid. Calibration was considered successful if fixation errors were under 0.5°.

Eye tracking data were preprocessed and missing samples were imputed using published standardized routines[88]. The percentage of imputed samples was logged as an objective quality measure for potential subsequent participant exclusion (proportion of valid eye tracking samples during the fMRI–pupillometry assessment (mean ± standard error): 0.803 ± 0.024).

*Magnetic resonance imaging*

MRI data were collected using a 3T Magnetom TIM Trio (Siemens Healthcare) with a 12-channel head coil.

An axial, T1-weighted neuromodulation-sensitive Fast Spin Echo (FSE) sequence was collected to assess markers for locus coeruleus integrity. The following parameters were used[41,89]: acquisition matrix: 440 × 512, 10 slices, voxel size: 0.5 × 0.5 × 2.5 mm, 20 % gap between slices, repetition time (TR): 600 ms, echo time (TE): 11 ms, flip angle (FA): 120 °, acquisition time: 11:48 min. To increase signal to noise ratios in brainstem imaging, the sequence included four online averages and yielded two images, extracted locus coeruleus parameters were averaged to boost stability of estimates[48].

In addition, a sagittal T1-weighted Magnetization-Prepared Gradient Echo (MPRAGE) sequence with the following parameters was collected to facilitate co-registration to standard space: acquisition matrix: 256 × 256 × 192, voxel size: 1 mm isotropic, repetition time (TR): 2500 ms, echo time (TE): 4.77 ms, inversion time (TI): 1100 ms, flip angle (FA): 10 °, acquisition time: 9:20 min.

Finally, a T2*-weighted whole-brain Echo Planar Imaging (EPI) sequence was used to track blood oxygenation level dependent (BOLD)-changes during the conditioned oddball task. The following imaging parameters were used: acquisition matrix: 72 × 72, 36 slices, 450 images, voxel size: 3 mm isotropic, repetition time (TR): 2000 ms, echo time (TE): 30 ms, flip angle (FA): 80 °, acquisition time: 15 min.

MPRAGE and EPI data were preprocessed using standardized routines as implemented in HeuDiConv[90], MRIQC[91,92], and fMRIprep[93] and as detailed in the supplementary information. Data were transformed to 2 mm isotropic MNI 152 non-linear 2009c asymmetric space and smoothed with an isotropic 8 mm full-width half-maximum (FWHM) kernel for further analyses, following recommendations for smoothing kernels to be at least twice the voxel resolution[94]. A time series of confounds was derived from head-motion estimates, and global signals (within the white matter, the cerebrospinal fluid (CSF) and whole brain mask). These confounds were expanded with the inclusion of temporal derivatives and quadratic terms for each, yielding a total of 36 confounds that were included in within-participant analyses[95,96].

*Physiological data analyses*

*Pupillometry analysis*

Pupil time series were analyzed using the EEGlab[97], eye-EEG[98], and fieldtrip[99] toolboxes. The continuous pupil time series were segmented into trials surrounding presentation of the Gabor patches (for conditioning and oddball experiments). Within-participant trial-level analyses then contrasted pupil responses across experimental conditions after baseline correction (–500–0 ms relative to stimulus onset). That is, for conditioning experiments, CS+ and CS– trials were contrasted, while for the oddball experiments standard and oddball trials were compared (i.e., collapsing the two oddball categories) using sample-wise independent samples *t*-tests. Within-participant analyses were repeated over $n_{Bootstraps}$ = 50 and the resulting *t*-value time series were averaged[38]. Subsequent across-participant analyses tested for the consistency of within-participant effects on a group level (dependent samples *t*-test against zero), while controlling for multiple comparisons using cluster-based random permutation tests[100]. For more details, see[38].

*Functional magnetic resonance imaging analysis*

fMRI data were analyzed using the Statistical Parametric Mapping (SPM) 12 toolbox[101] to identify brain responses to oddball stimuli. Within-participant event-related analyses included stick functions for each stimulus onset (standards, oddballs) convolved with a canonical hemodynamic response function as well as its temporal and dispersion derivatives[102]. General linear models contrasted BOLD responses to standard and oddball stimuli (aggregating over the two oddball categories to increase power). Subsequent across-

participant analyses evaluated the consistency of within-participants effects on a group level with family-wise error correction for multiple comparisons.

Overlap of observed group-level effects with several published functional network atlases (see Figure 3,[23,58,59]) was evaluated using Dice coefficients and permutation tests, as implemented in the Network Correspondence Toolbox[24]. For overlap estimations, statistical maps were thresholded at $T = 3$.

Follow-up within-participant functional connectivity analyses first calculated trial-by-trial activation patterns for each voxel[76] and next assessed which brain regions' time series correlated with the locus coeruleus[77]. For this, a locus coeruleus consensus mask was applied as seed region[75] that reliably segmented the locus coeruleus-related hyperintensity in this study, as shown in the results. That is, our functional connectivity analyses were centered on the region in which we localized the locus coeruleus using dedicated high-resolution structural scans.

We detected a reliable association of locus coeruleus and anterior insula time series. To further characterize the temporal properties of this association, we estimated cross-correlations between TR-level locus coeruleus and insula time series on a participant level (using *crosscorr* in *Matlab*;[30]). To this end, we averaged BOLD signals across voxels within the locus coeruleus consensus mask[75], as well as anterior insula functional-connectivity cluster. Cluster-based random permutation tests probed the consistency of the participant-level cross-correlation estimates on a group level after de-meaning[100].

*Structural magnetic resonance imaging analysis*

Neuromodulation-sensitive FSE images were analyzed using a previously established semi-automatic procedure to extract proxies for locus coeruleus integrity[41,75,89] using Advanced Normalization Tools (version 2.3.3.; ANTs[103,104]).

In brief, first MPRAGE scans were linearly resampled to 0.5 mm isotropic resolution before estimating a whole-brain group template (six iterations; *antsMultivariateTemplateConstruction*, including *N4BiasFieldCorrection*). Next, native-space FSE scans were non-linearly aligned to within-person template-space MPRAGE images using *antsRegistrationSyNQuick* to facilitate subsequent brainstem template construction based on the outputs of this transformation (six iterations; *antsMultivariateTemplateConstruction*, including *N4BiasFieldCorrection*). Finally, the brainstem template was moved to 0.5 mm linear MNI space using the whole-brain template as an intermediate target (*antsRegistration*, facilitated by a custom coregistration mask). All transformation matrices were then concatenated and applied to individual neuromodulation-sensitive FSE scans, bringing them directly from native to MNI space in a single step (*antsApplyTransforms*).

To extract proxies for locus coeruleus integrity, standard space FSE images were masked using a high-confidence locus coeruleus consensus mask[75] that captured the observed locus coeruleus hyperintensity well (see Figure 6). To normalize intensity values for across-participant analyses, scans were also masked with a pontine reference area mask[75]. The peak voxel intensity for each slice of each region of interest was then automatically identified. Finally, intensity ratios for each slice of the locus coeruleus were computed as a measure of structural integrity (see Equation 1). For each slice, these ratios were derived by dividing the difference between the peak intensity in the locus coeruleus and the corresponding reference region by the peak intensity of the reference region, following previously established methods[41,75,89].

**Equation 1:**

$$LocusCoeruleusRatio = \frac{\max(LocusCoeruleus) - \max(Reference)}{\max(Reference)}$$

For subsequent analyses, extracted slice-wise values were averaged over hemispheres and then the peak value across slices was selected, while excluding the two most rostral slices to avoid unreliable intensity values at the edge of the acquisition[41].

*Behavioral data analysis*

In the conditioned oddball task, participants were instructed to press a specific button corresponding to the orientation of the presented Gabor stimulus. The majority of trials (70%) featured the standard stimulus, creating a high probability that a standard stimulus would follow another standard stimulus. We assumed that due to this consistency participants would build up a tendency (bias) to respond with the corresponding key. We termed these *stay-standard* trials. Occasionally, this expectation was violated by the presentation of one of the oddball stimuli, requiring participants to switch response keys (*switch-to-oddball trials*). Following an oddball stimulus, most trials returned to the standard stimulus (*switch-to-standard*), while less frequently, another oddball appeared (*stay-oddball*). Following this reasoning, we estimated mean reaction times for each of these four trial categories for each participant (2 (stay/switch) × 2 (standard/oddball)) after log-transformation and *Z*-standardization of reaction times across trials.

Crucially, participants began the task without prior knowledge of the statistical structure or trial distribution. The extent to which participants adjusted their behavior over time in response to the predictability of the stimuli is thus interpreted as an implicit measure of (task structure) learning. To quantify if participant indeed learned the statistical structure of the task, we down-sampled the trial-level reaction-time time series of the repeated oddball experiments (320 trials in total, two repetitions of 160 trials each; cf. Figure 7). That is, we averaged reaction times over 10 adjacent trials within the four trial categories, yielding 32 reaction-time time bins, which we contrasted across trial categories. Finally, we evaluated if participants over the course of the experiment developed a tendency to preferentially focus on one trial category at the expense of another. To this end, we probed if the contrast of reaction times (*switch-to-oddball – stay-standard*) increased over time. We repeated these analyses on a group level (correlation of group-averaged reaction time contrast and time bin) and on a single-participant level (linear regression predicting reaction time contrasts by time bin). Finally, participant-level beta estimates (quantifying implicit learning) were contrasted against zero using dependent-samples *t*-test to evaluate the consistency of implicit learning on a group level.

*Multimodal data analyses*

*Combined pupillometry–functional magnetic resonance imaging analyses*

Presentation of oddball stimuli elicited pupil dilation and distributed cortical activation, including the action-mode network. To test which brain regions' activation scaled with pupil-indexed neuromodulation, we estimated a separate set of general linear models. First, we down-sampled each participant's pupil time series to the fMRI temporal resolution (TR = 2 s) and added it as regressor to the participant-level models[105]. The same confounds as in unimodal fMRI analyses were applied (see above), while task regressors were omitted. Subsequent analyses across participants assessed the consistency of within-participant effects at the group level, applying family-wise error correction to account for multiple comparisons. These analyses were restricted to participants with high-quality pupil data (>50% valid non-imputed samples; 64/71 participants[88]).

*Association of pupillometry–functional magnetic resonance imaging patterns and PET-derived transporter maps*

Combined pupillometry–fMRI analyses showed that brainstem–midbrain and insula activation correlated with pupil size variations, suggesting neuromodulatory influences. To

more directly test this, we leveraged publicly available maps of neuromodulatory transporter distributions[56]. PET-derived maps were resampled to the spatial resolution of our pupil–fMRI activation patterns (2 mm MNI-ICBM 152 non-linear 2009 version c space). Next, we probed the voxel-wise association of noradrenergic transporter expression and pupil-linked BOLD activation using two alternative transporter maps using Pearson's correlations[56,65–69]. To judge the reliability of these effects, we ran two negative control analyses, using two maps of GABAergic receptor distribution acquired from two different sources[70,71] as well as two comparative analyses, using maps of the dopaminergic [74] and serotonergic transporter[73] distribution. For each of these, observed effects were contrasted to reference distributions of correlation coefficients estimated with permuted pupillometry-fMRI data while preserving the spatial autocorrelation of the observed data. Specifically, we applied a phase-randomization approach, which retains the power spectrum of the original data while randomizing its phase in the Fourier domain[106]. This method generates surrogate datasets that maintain the autocorrelation properties of the original data (i.e., the pupil–fMRI activation map) while breaking voxel-wise correspondences with the PET-derived transporter/receptor maps. We computed correlation coefficients between the shuffled pupil-linked BOLD activation pattern and the transporter/receptor maps across 10000 iterations, forming a null distribution, to which we compared the observed correlation coefficients.

Finally, to determine if the voxel-wise noradrenergic transporter expression explained variance in pupil-linked BOLD patterns (*PupilBOLD*), we used multiple regression analyses (using *fitglm* in Matlab). Specifically, we compared a base model (*PupilBOLD* ~ 1 + *5HTT* + *DAT*) incorporating the serotonergic (*5HTT*) and dopaminergic (*DAT*) transporter expression to a full model including all three neuromodulatory systems (*PupilBOLD* ~ 1 + *5HTT* + *DAT* + *NAT*). To obtain a single noradrenergic transporter predictor (*NAT*), the two available maps were averaged[65,69]. Differences in model fit between base and full models were evaluated using a likelihood-ratio test and compared to a null distribution obtained from adding shuffled noradrenergic transporter predictors (10000 iterations).

*Combined brain–behavior analyses*

Our physiological analyses yielded multiple locus coeruleus-related measures (MRI-indexed locus coeruleus integrity; pupil-indexed neuromodulation; locus coeruleus-linked action-mode network activation). Given the prominent involvement of the noradrenergic system in learning and memory [3], we next tested if these explained individual differences in implicit learning during the conditioned oddball task, using partial least squares correlations (PLSC[107,108]).

In short, partial least squares correlation is a multivariate statistical technique used to identify patterns of covariance between two sets of variables. In this study, behavioral partial least squares correlation was applied to explore the relationship between locus coeruleus-related measures and task-derived measures of implicit learning. By decomposing the covariance structure with Singular Value Decomposition, partial least squares correlation identifies latent variables (LVs) that maximize the shared variance between the datasets (i.e., locus coeruleus-related measures and implicit learning). Each latent variable is characterized by a pair of weighted combinations of variables—one from each dataset—allowing for the assessment of how strongly these patterns are expressed across participants. Statistical significance of the latent variables was determined using permutation tests ($n_{permutations}$ = 10,000), and the reliability of individual variable contributions was evaluated with bootstrapping ($n_{bootstraps}$ = 10,000). A ratio of a variable's weight and its bootstrapped standard error, termed bootstrap ratio, (BSR), allows identifying indicators reliably contributing to the latent variable ($|BSR| \geq 1.96$, interpreted analogous to Z-scores). Taken together, partial least squares correlation provides a robust method for examining complex, high-dimensional

relationships, integrating locus coeruleus-related and learning-related measures. For further details, see[75].

The following neural and behavioral variables were used as input to the partial least-squares analyses: (1) individual task-related left anterior insula activations, extracted using MarsBar[109], averaged over voxels of the cluster that showed reliable associations with pupil-linked neuromodulation (Figure 4); (2) individual task-related pupil dilation, extracted using the cluster shown in Figure 2 and averaged over samples; (3) peak locus coeruleus contrast ratios, averaged over hemispheres; and (4–8) individual reaction times for each trial category, 2 (stay/switch) × 2 (standard/oddball), averaged over trials after log-transformation and *Z*-standardization, as shown in Figure 7. All input variables were standardized across individuals, and participants with absolute values >3 were dropped before analyses (n = 3). Post-hoc independent samples *t*-tests probed age differences in the latent brain and behavioral variables. As a sensitivity analysis, we replicated partial least squares-correlation findings using a simpler analytical strategy that averaged over standardized neural indicators (i.e., calculated composite scores based on (1)-(3), see PLSC analyses), estimated the difference in response times for oddball and standard trials, and then correlated these measures.

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**Author contributions**

MJD, MM and MWB designed the study. MJD performed the experiments together with a team of research assistants. MJD and TL analyzed the data. MJD wrote the paper. All authors gave conceptual advice and revised the paper.

**Competing interests**

The authors declare no competing interests.

**Data availability**

Participants in this study did not consent to the public sharing of their data. To obtain access to participant-level data, please contact the corresponding author (MJD) with a signed data sharing agreement (template available at: https://osf.io/4t5hj/). Un/thresholded group-level data are available at https://osf.io/4t5hj/.

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