Anxiety is associated with reduced pupillary response to volatility

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Abstract:

This study examines how individuals distinguish and adapt to volatility and noise, and whether mood disorders modulate such adaptation. Fifty healthy participants were recruited based on varying depression levels and completed a coin catching task under varying volatility and noise conditions. Learning rates (LRs) and pupil responses served as behavioral and physiological adaptation indicators. As expected, results showed increased LRs under high volatility and decreased LRs in noisy conditions. Pupil dilation tracked environmental volatility but was not significantly affected by noise. Notably, higher trait anxiety correlated with reduced pupillary reactions to volatility. The findings suggest that humans normatively adjust to environmental uncertainties, and mood disorders might influence this adaptability. The study enhances understanding of individual differences in learning under uncertainty and the impact of affective states on such processes.

Keywords: uncertainty; reinforcement learning; computational psychiatry

Introduction

Learning in an uncertain environment is a fundamental part of cognition. Various types of uncertainties influence learning in distinct ways. In particular, in a volatile environment, one should increase how much one learn from recent observations and do the reverse when the environment is noisy. The noradrenergic and cholinergic systems, which are also implicated in controlling pupil dilation, are theorized to signal environmental volatility and noise, respectively (Yu & Dayan, 2005). Individuals with high levels of anxiety have difficulty adapting to volatility (Browning et al., 2015), although this association has never been tested in situations where both the volatility and noise vary.

This study aims to explore how individuals adjust to volatility and noise and to examine the association of these adaptations with mood disorder symptoms at both behavioral and neural levels. At the behavioral level, we hypothesize that people will (H1) increase LRs when environment is volatile and (H2) decrease LRs when environment is noisy. We also hypothesize that (H3) pupil diameter increase when environment is volatile and (H4) decrease when environment is noisy. Furthermore, we hypothesize that (H5) individual with higher levels of depression will exhibit diminished pupil dilation in response to volatility.

Methods

Sample

We prescreened and recruited 50 healthy participants based on their depression symptoms, as measured by Epidemiologic Studies Depression Scale (CES-D), to obtain a sample of individuals with low (CES-D < 10; n = 14), medium (10 < CES-D < 20; n = 20), and high depressive symptoms (CES-D > 20; n = 16). Eight participants were excluded in the analysis due to missing pupillometry data.

Experimental Paradigm

We used a ‘coin catching task’, where participants catch coins released from a circle's center using a draggable bucket. The study featured a 2x2 design varying volatility (high/low) and noise (high/low), resulting in four blocks with 50 trials each. Coin landing positions were determined by a von Mises distribution, with noise levels manipulated through distribution dispersion and volatility controlled by a von Mises random walk affecting the distribution's mean.

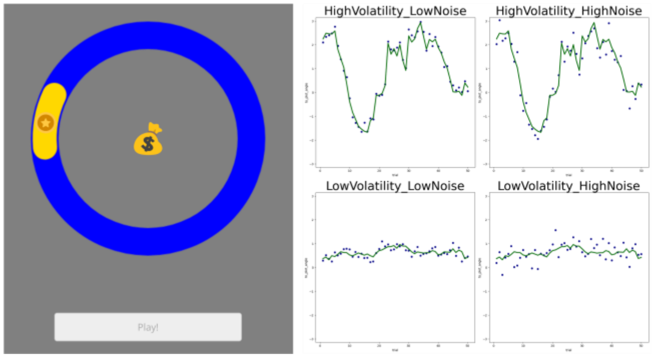

Figure 1: The schedule used in the coin catching task follows a 2x2 factorial design.

Questionnaires

Apart from the CES-D used in the pre-screening, we also included three other questionnaires to assess participants depressive and anxiety levels –State Trait Anxiety Inventory- Trait (STAI-T), Work and Social Adjustment Scale (WSAS), and Temporal Experience of Pleasure Scale (TEPS).

Analysis

Computational Model We compared the fit of two models across participants (BIC and data features). The winning model contains four free parameters. Following the Rescorla-Wagner learning rule, people learn their estimate of where the coin will land from trial-wise prediction error with an update-rate $LR_{baseline}$. Additionally, we assume that people are also tracking temporal trends in the observed data: specifically, they are learning how much has the coin location changes from one trial to the next (represented as Δ below; updating with rate LR_{Δ}). The belief about coin location is a weighted average between $LR_{baseline}$ and LR_{Δ}, combined by *mixture parameter (a).*

$$Belief\theta_{t+1} = Belief_t + LR_{baseline} * (Outcome_t - Belief_t)$$
$$Belief\Delta_{(t+1)} = Belief\Delta_{(t)} + LR_\Delta * (\Delta - Belief\Delta_{(t)})$$
$$Belief_{t+1} = Belief_\theta(t+1) + a * Belief_\Delta(t+1)$$

The estimated LRs were then transformed into choice probability using von mises probability density function with a precision parameter.

$$Prob\ (choice|lr\theta,\ lr\Delta, a,\ precision) = \frac{\exp(precision\ * \cos(choice\ - belief))}{2\pi I_0(precision)}$$

Behavioral Analysis The main outcome measures were learning rate (LR) and learning rate adjustment (LR in high volatile blocks – LR in low volatility blocks; LR in low noise blocks – LR is high noise blocks). Outcome measure were analyzed using repeated measure ANOVAS, with Volatility (High vs Low) and noise (High vs Low) as the main factors of interest.

Pupil Dilation Analysis Pupil dilation was analyzed by regressing mean-centered volatility and noise, along with fatigue (indexed by trial number), on 7000 1ms time bins spanning from 2 seconds pre-outcome to 5 seconds post-outcome. We included an interaction term between volatility and noise and assessed the significance of effects using t-tests on the time-series beta weights.

Results

People adapt to noise and volatility normatively.

As hypothesized, participants increased their baseline LRs ($LR_{baseline}$) when volatility is high (F(1, 41) = 128.316, p < 0.001) and when noise is low (F(1, 41) = 11.916, p = 0.001). There was no significant interaction between noise and volatility. We did not observe any effect of volatility or noise on LR_Δ. Yet, we observed a significant volatility and noise effect on the mixture parameter (a) (F(1, 41) = 23.898, p < 0.001; F(1, 41) = 15.618, p < 0.001), participants' estimates of coin position was influenced by their estimate of temporal trends more when the environment was volatile and less when the environment was noisy. These effects are consistent with H1 and H2, where people learn less from recent observations when changes in coin locations are mostly due to chance.

Pupil dilation tracks volatility.

We observed that pupil dilation varied with volatility (t(41) = 3.591, p = 0.006) but not noise (t(41) = 1.137, p = 0.168). There was an interaction effect between noise and volatility (t(41) = -3.204, p = 0.001), indicating that high volatility and high noise and low volatility and low noise had a negative effect on pupil dilation. Additionally, increasing fatigue was linked to reduced dilation over time (t(41) = -3.736, p = 0.008). We also found a correlation between LR_Δ adjustment to volatility and volatility beta weights (r = 0.345, p = 0.025), suggesting that pupil dilation may be mirroring the temporal trends in the observed data.

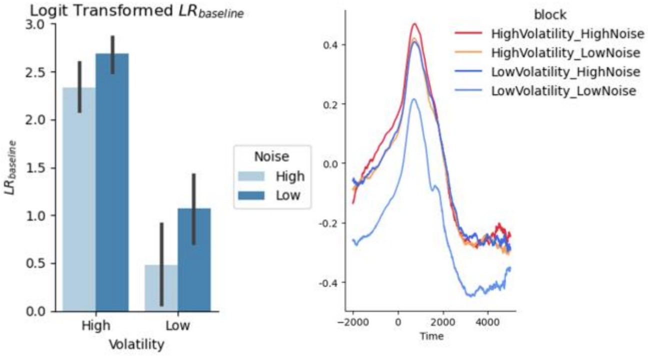

Figure 2: We observed that people adapt normatively to noise and volatility. Environmental volatility dilates pupils but not noise.

Higher trait anxiety is associated with reduced pupillary response to volatility.

Higher trait anxiety was associated with a decreased pupil response to volatility (r = -0.385, p = 0.012). Such relationship holds when we control for symptoms of depression, measured by CESD and WSAS by running a partial correlation ($r_{partial}$ = −0.395, p = 0.012). Yet, we did not observe any significant correlation between trait anxiety and $LR_{baseline}$ or LR_Δ.

Discussion

In line with previous findings, we found people adapt normatively to volatility (H1), and volatility has a positive effect on pupil dilation (H3). Though we find people reduce their $LR_{baseline}$ when noise is high (H2), we did observe any significant effect of noise on pupil dilation, contrary to what we hypothesized in H4. Lastly, we have shown that higher trait anxiety is associated with reduced pupillary response to volatility (H5).

The link between trait anxiety and reduced pupillary adaptation to volatility reveals how anxiety may skew the perception and learning of higher-order patterns in the environment, suggesting a target for interventions in anxiety disorders.

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References

Angela, J. Y., & Dayan, P. (2005). Uncertainty, neuromodulation, and attention. Neuron, 46(4), 681-692.

Browning, M., Behrens, T. E., Jocham, G., O'reilly, J. X., & Bishop, S. J. (2015). Anxious individuals have difficulty learning the causal statistics of aversive environments. Nature neuroscience, 18(4), 590-596.

Nassar, M. R., Rumsey, K. M., Wilson, R. C., Parikh, K., Heasly, B., & Gold, J. I. (2012). Rational regulation of learning dynamics by pupil-linked arousal systems. Nature neuroscience, 15(7), 1040-1046.

Pulcu, E., & Browning, M. (2019). The misestimation of uncertainty in affective disorders. Trends in cognitive sciences, 23(10), 865-875.

Vaghi, M. M., Luyckx, F., Sule, A., Fineberg, N. A., Robbins, T. W., & De Martino, B. (2017). Compulsivity reveals a novel dissociation between action and confidence. Neuron, 96(2), 348-354.