Title: Temporal stock market dynamics are related to fluctuations in population mood and brain morphometry.

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Summary:

A number of previous studies have indicated that market and population well-being are related. Using UK-biobank data we first identified a significant association between a local stock market index (FTSE100) and mood of 479,791 subjects and demonstrated that FTSE100 exhibits significant associations with volumetric measures of the brain regions involved in affective processing in 39,755 subjects with more distant markets exhibiting a weaker relation to these regions. These effects were primarily observed in the low-frequency band and were magnified over larger time-scales. The main results survived adjustments for seasonal effects, demographic confounders and effects of non-UK markets. The magnitude of these associations was also related to the strength of UK's social and economic ties to other countries. Finally, the main finding was replicated in an independent set of individuals from a different country. After identifying scale-free properties in the stock market time-series, we show that 1/f pink noise explains a large proportion of the market-brain variance. However, all results withstood the adjustment for the scale-free noise. Taken together, our results suggest how global dynamics in the society generalise to population mood and large-scale biological data.

Keywords: stock market, affective brain, collective mood, rewards, losses

Main Text

Previous research has suggested that changes in capital market evolution exhibit a strong impact on traders' emotional states [1], and are associated with the well-being of individuals who have no direct involvement in the stock market [2]. Moreover, it has been suggested that stock market turbulence is linked to increased anxiety [3], self-harm and suicide rates [4–6] and an elevated number of fatal car accidents [7]. These effects may be particularly pronounced in long-lasting financial crises, such as the 2008 stock market crash or the economy slowing in the COVID19 pandemic.

To date, there are no studies that have investigated the association of market behaviour with brain function and structure. In a broader perspective, one study has previously demonstrated how a single extreme aversive global event may impact fear circuits by linking individuals' geographical proximity to the site of 9/11 terrorist attacks to the reactivation of the amygdala during memory recollection [8]. Similarly, an upcoming study also suggests that intense experience of the COVID19 outbreak is associated with a volumetric increase of the amygdala [9].

The present study aims to understand whether more subtle but frequently occurring global events may leave a trace in the human brain on a population level. Here, we investigated how day-to-day fluctuations in the stock market are associated with brain structure. Since such fluctuations also mirror global socioeconomic changes in the society [10], the investigated associations imply a broader perspective than the specific effects of the market per se.

To do this, we accessed structural MRI data of 39,755 UK citizens from the UK Biobank acquired over approximately 5.5 years (between 2014-05-02 and 2019-10-31), and matched the scan date with the corresponding Financial Times Stock Exchange 100 Index (FTSE100) characterizing stock price of the top 100 UK companies with the largest revenue as our main independent variable (**Fig. 1,** see **Supplement Fig. S1** and **Table S1** for description of the whole dataset, which also included mood data collected over a period of approximately 14 years). The FTSE100 was chosen because the study subjects resided in the UK, and local changes in the economy were expected to impact brain structure on a population level most strongly. In order to index effects on the brain, daily time-series of the market capital index was matched with neuroimaging data focusing on a set of preregistered (https://osf.io/h52gk) brain regions known to play key roles in the processing of rewards and losses, as well as threat and fear [11–14]: amygdala, nucleus accumbens, insula, anterior, subcallosal and dorsal cingulate and lateral orbitofrontal cortical areas. Abnormal functioning of these circuits has also been documented to play a key role in the pathophysiology of anxiety and depression [15–18].

Previous research suggests that brain morphometry is capable of capturing plastic changes that happen after weeks [19] or days [20] of engagement of the relevant brain networks. Moreover, even acute activation of brain networks is associated with noticeable alterations in morphometric measures [21]. Even though these changes may represent widely different underlying mechanisms depending on observational time-scales, the literature supports the idea that grey matter changes in major brain networks parallel their functional reorganization [22].

Prior to the main analysis, we attempted to replicate previous behavioural findings suggesting a relation of market fluctuations with mood and well-being [2,5,23,24] on a large sample from the UK Biobank data (n = 479,791) collected over a period of approximately 14 years. Analysing the relations between FTSE100 and self-reported measures of emotional well-being we confirmed that market ups (higher FTSE100 scores) were associated with higher scores of "happiness" and lower scores in self-reported "negative emotions": irritability, hurt and nervous feelings, anxiety (**Table 1**). The identified association also held true for the 5.5-years of the MRI subsample (**Supplement Table S2**).

Table 1. Subjective well-being and FTSE100 scores: 14 years period

	Linear Mixed-Effects			**Effect-sizes, Pearson r (95% C.I.)**		
	β_{std}	*T(df)*	p_{fdr}	***Raw***	***DayAVG***	***MonthAVG***
Negative Emotions (total)	-0.09	-27.85(7905)	<0.001	-0.12(-0.113.-0.099)	-0.23(-0.275.-0.185)	-0.598(-0.717.-0.445)
Irritability	-0.03	-7.58(7905)	<0.001	-	-0.068(-0.116.-0.021)	-0.202(-0.394.0.006)
Sensitivity/hurt feelings	-0.09	-25.51(7905)	<0.001	-	-0.233(-0.277.-0.187)	-0.467(-0.616.-0.287)
Nervous feelings	-0.06	-16.69(7905)	<0.001	-	-0.13(-0.177.-0.083)	-0.406(-0.567.-0.216)
Worrier/anxious feelings	-0.06	-18.83(7905)	<0.001	-	-0.171(-0.217.-0.124)	-0.325(-0.5.-0.126)
Happiness	0.06	16.9(7891)	<0.001	0.063(0.056.0.07)	0.156(0.109.0.202)	0.348(0.151.0.519)

β_{std} - standardized β coefficients, p_{fdr} – p-values corrected for multiple testing with false discovery rate. Subcomponents of negative emotions are binary variables (-), Day/MonthAVD – data averaged by days and months. The analyses leveraged random linear mixed effects framework with subject as a random effect, as a subset (n=1427) of the study subjects was assessed twice.

We then tested and confirmed our main hypothesis by showing that FTSE100 oscillations exhibited significant associations with the morphometry of the affective brain circuits. The most notable result was that bilateral amygdala, involved in threat detection and anxiety processing [14–18], showed a negative relation with the UK economic performance (**Fig. 1 and 2, Table 2,** whole-brain analysis is reported in **Supplement Fig. S2**).

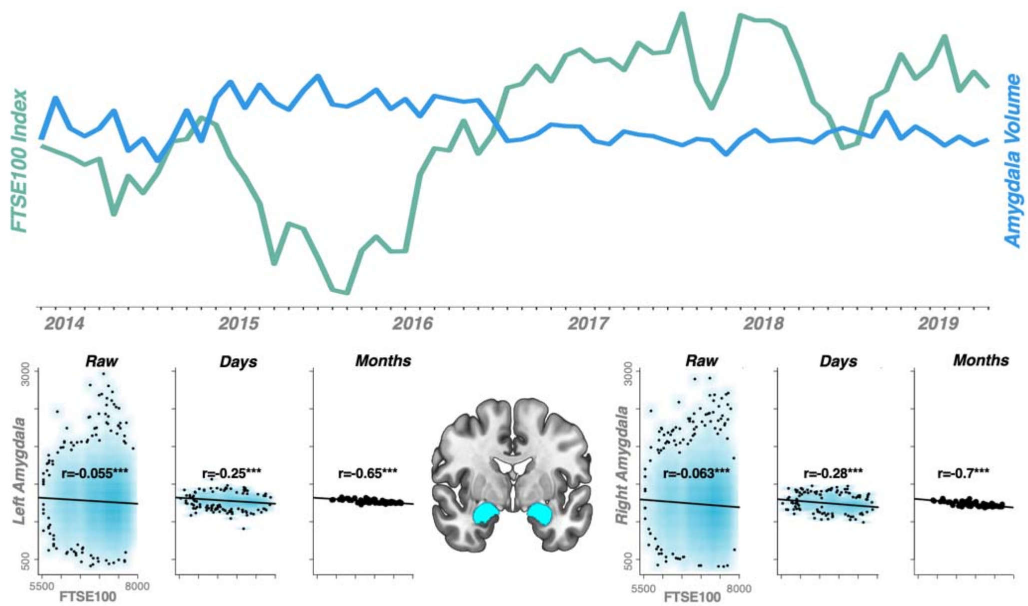

Fig.1** Studied brain-market associations. The figure illustrates the study rationale (top panel) and shows Pearson correlations (p<0.001) between FTSE100-index and amygdala volume (bottom panel).*

Table 2. Associations between FTSE100 and structural characteristics of the fear network: cortical and subcortical volumes.

Region	Linear Mixed-Effects			Effect-sizes, Pearson r (95% C.I.)		
	β_{std}	T_{883}	p_{fdr}	*Raw, n=30,775*	*DayAVG, n=1299*	*MonthAVG, n=66*
L Amygdala	-0.054	-9.51	<0.001	-0.055(-0.066,-0.043)	-0.253(-0.304,-0.202)	-0.615(-0.746,-0.439)
R Amygdala	-0.062	-10.91	<0.001	-0.063(-0.074,-0.052)	-0.282(-0.332,-0.231)	-0.644(-0.767,-0.477)
L Accumbens	-0.054	-9.54	<0.001	-0.055(-0.066,-0.044)	-0.232(-0.283,-0.18)	-0.623(-0.752,-0.449)
R Accumbens	-0.062	-10.89	<0.001	-0.064(-0.075,-0.052)	-0.259(-0.309,-0.207)	-0.662(-0.779,-0.5)
L LOFC	-0.026	-4.68	<0.001	-0.031(-0.042,-0.02)	-0.141(-0.193,-0.087)	-0.443(-0.619,-0.225)
R LOFC	-0.019	-3.49	0.001	-0.023(-0.034,-0.012)	-0.082(-0.136,-0.028)	-0.292(-0.499,-0.054)
L Insula	0.037	6.62	<0.001	0.042(0.031,0.053)	0.21(0.157,0.261)	0.494(0.286,0.657)

R Insula	0.032	5.86	<0.001	0.037(0.026,0.048)	0.187(0.134,0.239)	0.413(0.19,0.595)
L Subcallosal	0.018	3.18	0.002	0.02(0.009,0.032)	0.134(0.08,0.187)	0.322(0.087,0.524)
R Subcallosal	0.015	2.74	0.008	0.019(0.007,0.03)	0.129(0.075,0.182)	0.305(0.068,0.509)
L Anterior Cingulate	0.025	4.67	<0.001	0.035(0.024,0.046)	0.178(0.124,0.23)	0.408(0.184,0.591)
R Anterior Cingulate	0.024	4.44	<0.001	0.033(0.022,0.044)	0.169(0.116,0.222)	0.428(0.207,0.607)
L Paracingulate	0.004	0.8	0.426	0.001(-0.01,0.013)	0.044(-0.01,0.098)	0.106(-0.14,0.339)
R Paracingulate	0.005	0.83	0.426	0.003(-0.008,0.014)	0.052(-0.003,0.106)	0.122(-0.124,0.353)
Intracranial Volume	0.004	0.87	0.426	-0.009(-0.02,0.002)	-0.016(-0.07,0.038)	-0.098(-0.332,0.147)

Day/MonthAVG – data averaged over days and months. Intracranial volume (ICV) was selected as a reference measure, which was not expected to exhibit significant associations with global stock market behaviour. β_{std} *- standardized* β *coefficients,* p_{fdr} *– p-values corrected for multiple testing with false discovery rate. The analyses leveraged random linear mixed effects framework with subject as a random effect, as a subset (n=1427) of the study subjects was scanned twice.*

Thus, market downs were associated with increased amygdala volume. This result is in line with the effect of a single extreme aversive global event on amygdala fMRI response [8] and with the COVID19 pandemic experience on amygdala volume [9]. Here, we demonstrate that stock market oscillates together with morphometric characteristics of the threat and fear circuits on a population level.

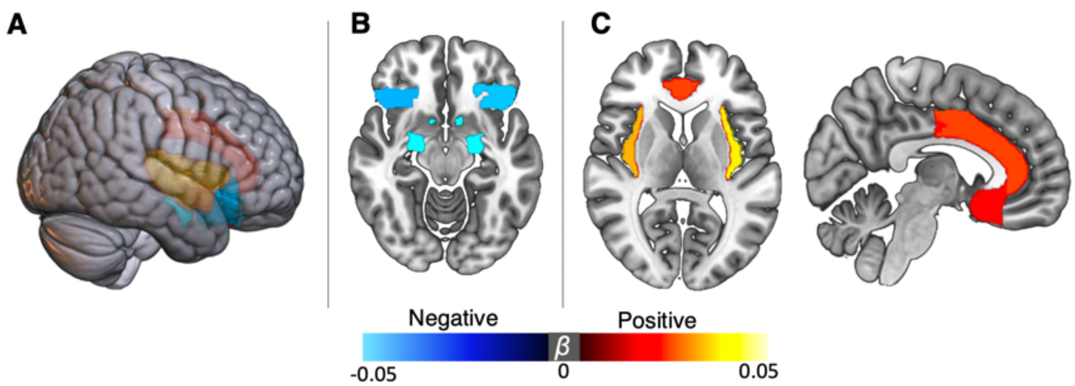

Fig. 2 *Regional profile of brain-market associations.*
A – three-dimensional view of the significant findings (p_{FDR}*<0.05). FTSE100 exhibited negative (B) associations with amygdala, nucleus accumbens and orbitofrontal cortex, whereas insular and cingulate regions were positively (C) associated with the index scores.*

The analyses leveraged random linear mixed effects framework with subject as a random effect, as a subset (n=1427) of the study subjects was scanned twice.

Similar findings were observed for nucleus accumbens and lateral orbitofrontal cortex (lOFC) (**Fig. 2**, **A** and **B**). While nucleus accumbens is mostly known for being involved in reward anticipation, it is equally important for processing losses [11,12]. lOFC has been suggested to be involved in processing expectations within the emotional domain [25–27], including losses and rewards [28,29]. Further supporting this, a significant interaction (β = -0.01, t_{776} = -2.87, p=0.004, p_{fdr} = 0.05) between FTSE100 and income index was found on the right lOFC volume (**Supplement Table S5**). Post-hoc analyses revealed the highest effects in individuals with the lowest and highest income, suggesting that right lOFC of those subjects is particularly sensitive to the capital market swings. Insula and anterior cingulate showed the opposite effect, i.e. the size correlated positively with the market (**Fig. 2**, **A** and **C**).

All regions mentioned above, except for lOFC, are involved in both positive and negative emotional processes [11–13]. Out of those regions, subcortical nuclei (amygdala and nucleus accumbens) correlated negatively with the stock market. In contrast, the cortical regions (insula and anterior cingulate) seem exhibit a positive relation with the stock market moves. The magnitude of the identified effects varied depending on time scale with median Pearson correlation $|r|$ = 0.033 (0.001-0.064) for the raw data, $|r|$ = 0.169 (0.017-0.282) for the day-averaged measures, and $|r|$ = 0.492 (0.09-0.73) when brain and market data were averaged over months (**Table 2**, **Fig. 1**). Importantly, all of the reported associations changed very little after detrending the FTSE100 time-series. Deconvolving FTSE100 time-series into low- and high-frequency domains using fast Fourier transform, showed that low-frequency oscillations mostly drive the effect, although, a similar pattern of associations was observed for the high frequency band (**Supplement Fig. S3, Table S6**).

We amended the preregistered protocol by adding additional possible confounding variables to confirm that the main results are robust and withstand correction for age, sex, presence of psychiatric diagnoses, seasonal effects (months) and intracranial volume (**Supplement Table S3**).

When considering the indexes of the UK's fifteen top trading partners [30], a similar pattern of associations as the one for FTSE100 was observed for the equivalent local European indexes (e.g. German GDAXI, Dutch AEX, French FCHI) but was of smaller magnitude (**Fig. 3**). The associations further declined or had different directions for markets that were more distant in a socio-economical dimension (as also reflected in a weaker correlation with FTSE100), including the reference Shanghai Composite Index (SSEC). Importantly, the results also withstood correction for these indexes (**Supplement Table S4**), which implies that the local economic performance captured by the FTSE100 exhibits a specific association with the characteristics of the scanned UK population.

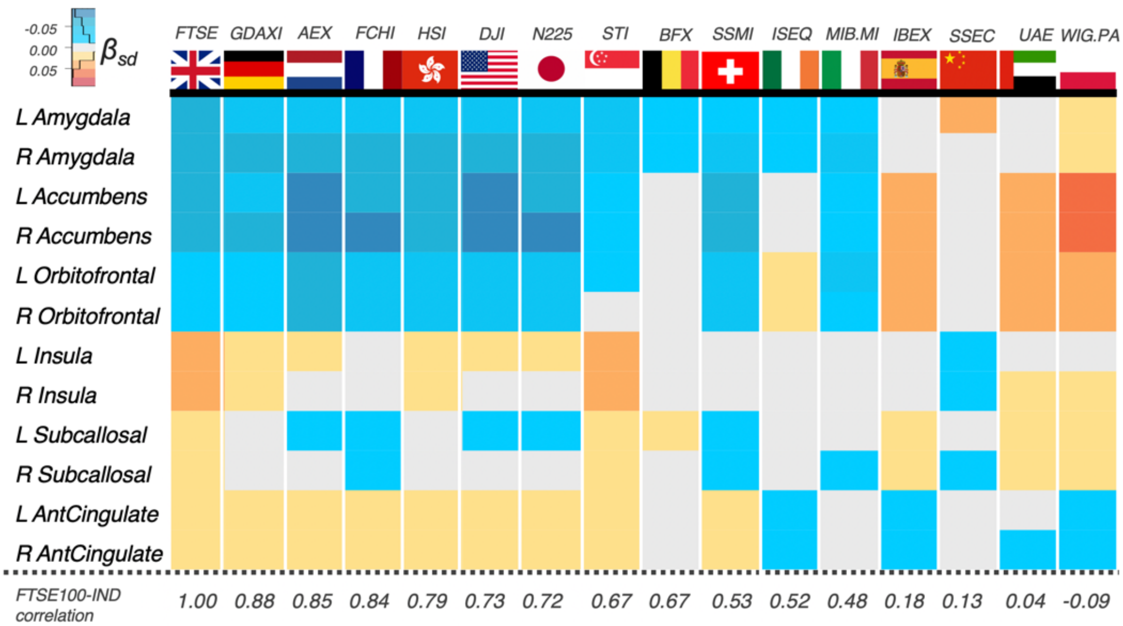

Fig. 3 *Pattern of brain-market associations for different capital market indexes. Strongest associations were found for the UK market index (FTSE100). Japanese and Singapore and Hong Kong indexes also exhibited a similar pattern of associations possibly reflecting socioeconomic and geographic similarity with the UK, whereas Dow Jones Industrial Average (DJA) likely reflects major contribution of the United States to the world economy. Chinese index (preregistered as a reference) had one of the weakest associations with the studied volumetric measures. FTSE100-IND correlations: Pearson correlation of FTSE100 with other investigated indexes. The* analyses leveraged random linear mixed effects framework with subject as a random effect, as a subset (n=1427) of the study subjects was scanned twice.

Regarding causality, two hypotheses exist that attempt to explain the direction of the mood-market relationships. The most widely accepted one states that population mood and well-being are impacted by market via effects on the socioeconomic environment [2,4,24]. These effects, heavily reinforced by media, may represent threat signals and subsequently impact brains and emotional states of the population [7]. However, an alternative hypothesis from socionomics is currently growing in popularity. It puts forward the idea of "social mood" as a herding-driven emergent state that originates from population dynamics and subsequently drives global processes, including economic crises, wars, art and fashion [10,31]. According to this hypothesis, social mood is an inherently hidden state of the society. It is related (but not identical) to the mood of individuals that such a group consists of. This hypothesis is by the data acquired in small-scale experimental studies demonstrating involvement of reward and fear circuits in future financial decisions [32–34].

To begin to disentangle between the two hypotheses, we evaluated associations with time-lagged Pearson correlation. We identified that brain volumes correlate higher with *earlier* market prices. The correlation remains significant for approximately one year and then gradually decays (**Fig. 4**). While an autocorrelation, as expected, is present in the stock market time-series [35] (**Supplement Table S7**), the fact that earlier economic data peaks with the brain volume implies that the market events may be antecedent to the brain volume fluctuations, offering initial evidence that the market impacts the brain, mood, and well-being. The same analyses were carried out on the monthly scale yielding similar results (**Supplement Fig. S4**) and also for the mood data with the FTSE100, but no clear antecedent relationship could be drawn for the latter (**Supplement Fig. S5**).

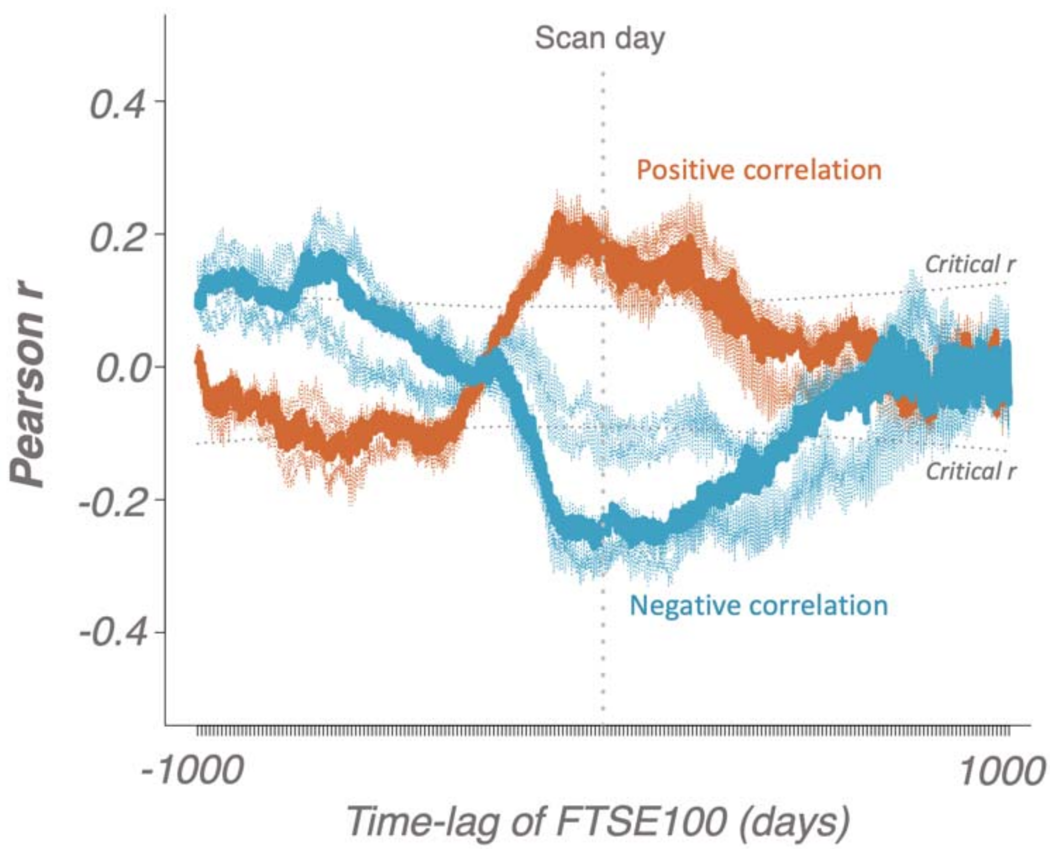

Fig. 4 *Pearson correlations for the brain and FTSE100-lagged data averaged over days. Transparent lines represent individual regions whereas thick lines represent medians of the correlations. Dotted boundaries represent critical r-values for α=0.001. The plot represents magnitudes of associations between brain data at the date of scanning and the FTSE100 index shifter forward (right) and backward (left) in time. Note a reversed peak for earlier dates reflective of autocorrelations.*

Despite the fact that Toda-Yamamoto implementation of Granger Causality tests specifically designed for serially correlated data [36] provided substantially stronger support in favor of a causal link "Market impacts Population Brain" (**Supplement Table S8**), a caution is still advised when interpreting these analyses due to 1/f noise present in the time-series (**Fig 5**). To illustrate the importance of this point we first show the absence of any significant effects after shuffling the dates (**Supplement Table S10**, column 1), but appearance of residual associations for the time-shifted data (**Supplement Table S10**, column 2, also seen on **Fig 4**). Importantly, simulating stock market data with 1/f noise produces a similar effect (**Supplement Table S10**, column 3), which, however, unlike the main results disappear after adjusting for other stock market indexes (**Supplement Table S10**, column 4) confirming that the main effect is not exclusively driven by the 1/f noise. To further demonstrate generalizability of the findings, we replicated the results on an independent set of 424 individuals from the US population (**Supplement Fig S6**). Moreover, we demonstrated that the magnitude of the brain-market links (measured as median squared root correlations) is related to economic and sociocultural ties of the UK to other countries (**Fig 6**).

Due to self-similarity properties identified in the data (**Fig 5**, right panel), we decided to conduct a series of noise simulation experiments. Simulating brain data with uniform and gaussian noise failed to induce the afore-mentioned correlations with FTSE100, but, as expected, they were more likely to be discovered for the brain data simulated with 1/f noise (**Fig 5**, left panel).

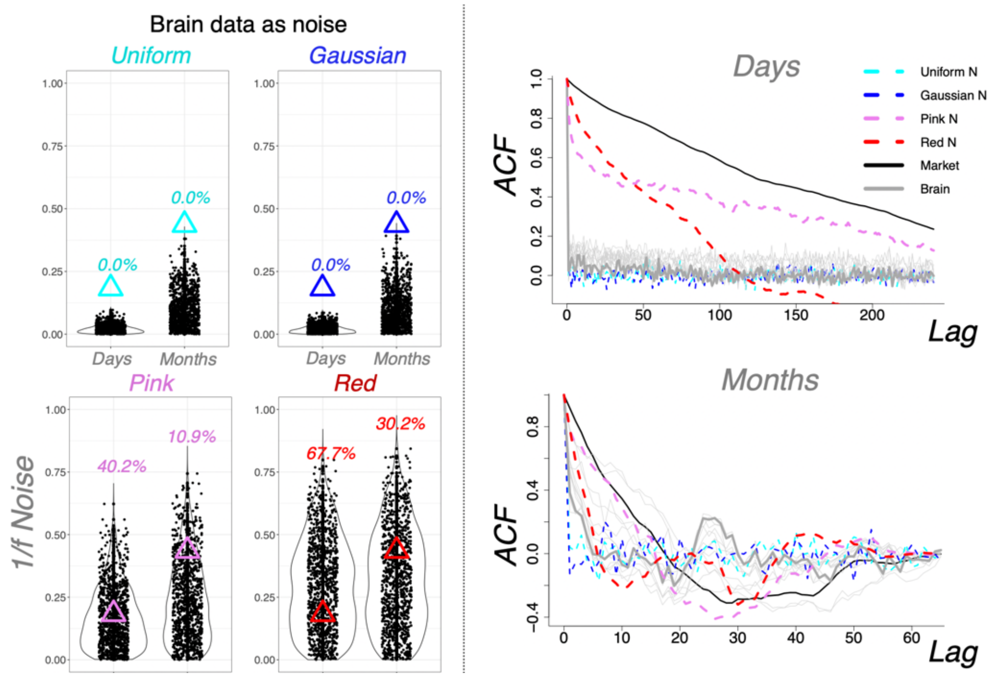

Fig 5*. Noise simulation experiments and autocorrelation function density plots.*

LEFT: Uniform and gaussian noise simulations failed to produce the effect sizes of equivalent magnitude to the one found in the present study (top). However, 1/f noise was capable of inducing these associations (bottom).

RIGHT: Autocorrelation function (ACF) density plots demonstrating scale-free properties of the stock market data most similar to the ones of pink noise.

Therefore, it appears so that scale-free noise is impacting populations at different levels, which is reflected in fluctuations of stock markets, mood and brains. To confirm this hypothesis, we repeated the simulations of brain data with 1/f noise and matched it with the stock markets of the UK's 15 top trading partners. We then subtracted the yielded Pearson correlations from the real ones and, as expected, the results withstood this correction (**Fig 6**, uncorrected effects are reported in **Supplement Fig S7**).

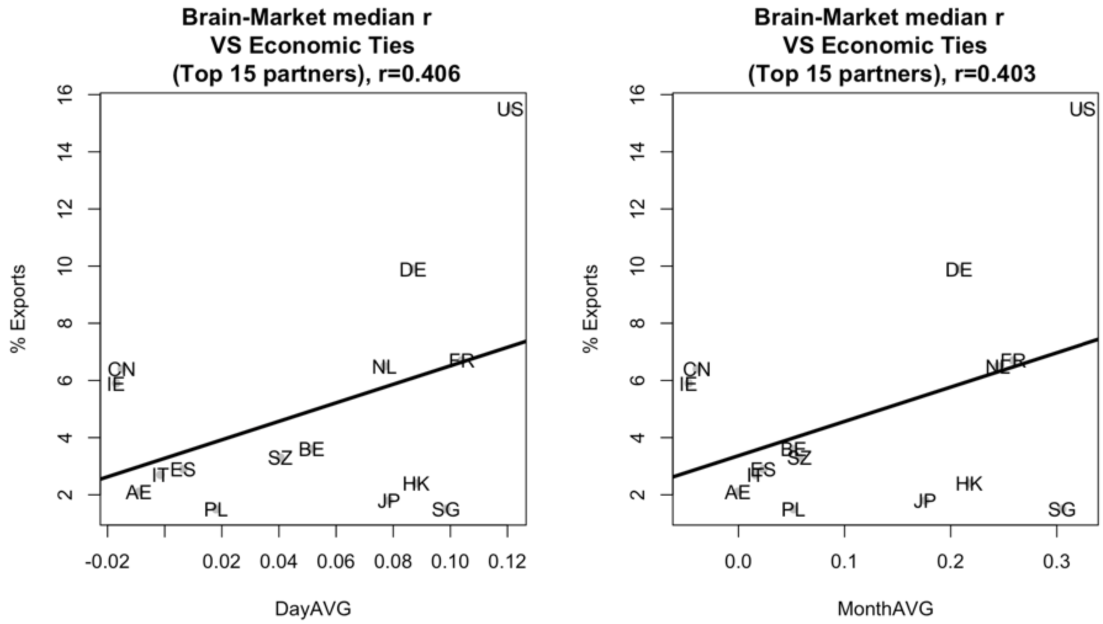

Fig. 6. *1/f-noise-corrected association between Brain-Market link and economic ties with 15 UK's top trading partners.*
The brain-market link was measured as median Pearson correlation (r) for all of the 12 regions that exhibited significant associations in the main analysis.
The strength of economic ties was measured as a relative percent of all exports.
Country labels: BE – Belgium, CN – China, FR – France, DE – Germany, HK – Hong Kong, IE – Ireland, IT – Italy, JP – Japan, NL – Netherlands, PL – Poland, SG – Singapore, ES – Spain, AE – United Arab Emirates, US – United States.

Importantly, a negative association was also identified for a number of sociocultural distances of the UK from 17 countries using data from Liu et al, 2018 [37] (**Supplement Fig S8**). All of the above supported Casti's hypothesis of stock markets as a metric stick for global societal dynamics [10].

Our study has a number of important limitations. First, we would still like to point the reader to the fact that most of our conclusions rely on random sampling assumptions and even despite the fact that our results survived all of the undertaken adjustments for potential analytical biases and confounds we cannot completely rule-out a possibility that these assumptions are not violated. To put it simply, temporal dynamics of the stock market may be linked to behavioural patterns of the population and thereby to enrolment likelihood of individuals with certain psychological and biological traits. In that case, the collected individual measures would inherently represent the consequences of the economic state and not a randomly drawn "snapshot" of the population. Scanner drifts represent a general limitation in studies performed over long time periods [38]. However, it is unlikely that our results are purely driven by them, first because these drifts are unlikely to behave like stock markets and second because we observed similar associations with the mood data.

Finally, we would like to highlight again that the investigated market variable (FTSE100 index) does not represent the stock market per se, but rather reflects a current socioeconomical state of the society.

Our study presented evidences for self-organized criticality present in stock market behavior supporting the socionomic hypothesis of "social mood" as a driving factor in global societal processes. Here we show that these dynamics may originate in scale-free temporal dynamics present in many complex systems in nature [35].

Despite being small on an individual level, these effects may have a large influence on a population level, as the previous studies have showed [2–7]. Moreover, our results suggest that some sub-populations are particularly vulnerable to economic turbulences, such as individuals with low and very high income. Understanding these complex but nevertheless important processes is of crucial relevance for sustainable and well-being-oriented economic development [39,40].

References:

1. Lo, A. W. & Repin, D. V. The psychophysiology of real-time financial risk processing. *J. Cogn. Neurosci.* **14**, 323–339 (2002).
2. Deaton, A. The financial crisis and the well-being of Americans. *Oxf. Econ. Pap.* **64**, 1–26 (2012).
3. Qin, X., Liao, H., Zheng, X. & Liu, X. Stock Market Exposure and Anxiety in a Turbulent Market: Evidence From China. *Front. Psychol.* **10**, 328 (2019).
4. Agrrawal, P., Waggle, D. & Sandweiss, D. H. Suicides as a response to adverse market sentiment (1980-2016). *PloS One* **12**, e0186913 (2017).
5. Lin, C.-L., Liu, T.-C. & Chen, C.-S. The association between attempted suicide and stock price movements: Evidence from Taiwan. *Psychiatry Res.* **254**, 323–331 (2017).
6. Wong, W. H.-S. *et al.* Stock Market Fluctuations and Self-Harm among Children and Adolescents in Hong Kong. *Int. J. Environ. Res. Public. Health* **14**, (2017).

7. Giulietti, C., Tonin, M. & Vlassopoulos, M. When the market drives you crazy: Stock market returns and fatal car accidents. *J. Health Econ.* **70**, 102245 (2020).
8. Sharot, T., Martorella, E. A., Delgado, M. R. & Phelps, E. A. How personal experience modulates the neural circuitry of memories of September 11. *Proc. Natl. Acad. Sci. U. S. A.* **104**, 389–394 (2007).
9. Salomon, T. *et al*. *Brain volumetric changes in the general population following the COVID-19 outbreak and lockdown*. http://biorxiv.org/lookup/doi/10.1101/2020.09.08.285007 (2020) doi:10.1101/2020.09.08.285007.
10. Casti, J. L. *Mood matters: from rising skirt lengths to the collapse of world powers*. (Copernicus Books, 2010).
11. Liu, X., Hairston, J., Schrier, M. & Fan, J. Common and distinct networks underlying reward valence and processing stages: A meta-analysis of functional neuroimaging studies. *Neurosci. Biobehav. Rev.* **35**, 1219–1236 (2011).
12. Oldham, S. *et al*. The anticipation and outcome phases of reward and loss processing: A neuroimaging meta-analysis of the monetary incentive delay task. *Hum. Brain Mapp.* **39**, 3398–3418 (2018).
13. Sescousse, G., Caldú, X., Segura, B. & Dreher, J.-C. Processing of primary and secondary rewards: A quantitative meta-analysis and review of human functional neuroimaging studies. *Neurosci. Biobehav. Rev.* **37**, 681–696 (2013).
14. LeDoux, J. E. & Pine, D. S. Using Neuroscience to Help Understand Fear and Anxiety: A Two-System Framework. *Am. J. Psychiatry* **173**, 1083–1093 (2016).
15. Bishop, S. J. Neurocognitive mechanisms of anxiety: an integrative account. *Trends Cogn. Sci.* **11**, 307–316 (2007).

16. Murray, E. A., Wise, S. P. & Drevets, W. C. Localization of dysfunction in major depressive disorder: prefrontal cortex and amygdala. *Biol. Psychiatry* **69**, e43-54 (2011).
17. Shah, S. G., Klumpp, H., Angstadt, M., Nathan, P. J. & Phan, K. L. Amygdala and insula response to emotional images in patients with generalized social anxiety disorder. *J. Psychiatry Neurosci. JPN* **34**, 296–302 (2009).
18. Stein, M. B., Simmons, A. N., Feinstein, J. S. & Paulus, M. P. Increased Amygdala and Insula Activation During Emotion Processing in Anxiety-Prone Subjects. *Am. J. Psychiatry* **164**, 318–327 (2007).
19. Draganski, B. *et al.* Changes in grey matter induced by training. *Nature* **427**, 311–312 (2004).
20. May, A. *et al.* Structural Brain Alterations following 5 Days of Intervention: Dynamic Aspects of Neuroplasticity. *Cereb. Cortex* **17**, 205–210 (2007).
21. Månsson, K. N. T. *et al.* Viewing Pictures Triggers Rapid Morphological Enlargement in the Human Visual Cortex. *Cereb. Cortex N. Y. N 1991* **30**, 851–857 (2020).
22. Zatorre, R. J., Fields, R. D. & Johansen-Berg, H. Plasticity in gray and white: neuroimaging changes in brain structure during learning. *Nat. Neurosci.* **15**, 528–536 (2012).
23. Cohen-Charash, Y., Scherbaum, C. A., Kammeyer-Mueller, J. D. & Staw, B. M. Mood and the market: can press reports of investors' mood predict stock prices? *PloS One* **8**, e72031 (2013).
24. Murgea, A. & Reisz, R. Does the market make us happy? The stock market and well-being. *West Univ. Timisoara* (2012).
25. Petrovic, P. Placebo and Opioid Analgesia-- Imaging a Shared Neuronal Network. *Science* **295**, 1737–1740 (2002).

26. Petrovic, P. *et al.* Placebo in Emotional Processing— Induced Expectations of Anxiety Relief Activate a Generalized Modulatory Network. *Neuron* **46**, 957–969 (2005).
27. Petrovic, P. *et al.* A prefrontal non-opioid mechanism in placebo analgesia: *Pain* **150**, 59–65 (2010).
28. Tanaka, S. C. *et al.* Prediction of immediate and future rewards differentially recruits cortico-basal ganglia loops. *Nat. Neurosci.* **7**, 887–893 (2004).
29. O'Doherty, J., Kringelbach, M. L., Rolls, E. T., Hornak, J. & Andrews, C. Abstract reward and punishment representations in the human orbitofrontal cortex. *Nat. Neurosci.* **4**, 95–102 (2001).
30. United Kingdom's 15 top import partners (Worldexports data). http://www.worldstopexports.com.
31. Prechter, R. R. *The socionomic theory of finance*. (2016).
32. Smith, A., Lohrenz, T., King, J., Montague, P. R. & Camerer, C. F. Irrational exuberance and neural crash warning signals during endogenous experimental market bubbles. *Proc. Natl. Acad. Sci. U. S. A.* **111**, 10503–10508 (2014).
33. Tong, L. C. P. *et al.* Trading experience modulates anterior insula to reduce the endowment effect. *Proc. Natl. Acad. Sci. U. S. A.* **113**, 9238–9243 (2016).
34. Gospic, K. *et al.* Altruism costs—the cheap signal from amygdala. *Soc. Cogn. Affect. Neurosci.* **9**, 1325–1332 (2014).
35. He, B. J., Zempel, J. M., Snyder, A. Z. & Raichle, M. E. The Temporal Structures and Functional Significance of Scale-free Brain Activity. *Neuron* **66**, 353–369 (2010).
36. Toda, H. Y. & Yamamoto, T. Statistical inference in vector autoregressions with possibly integrated processes. *J. Econom.* **66**, 225–250 (1995).
37. Liu, M., Hu, X. & Schedl, M. The relation of culture, socio-economics, and friendship to music preferences: A large-scale, cross-country study. *PLOS ONE* **13**, e0208186 (2018).

38. Poldrack, R. A. *et al.* Long-term neural and physiological phenotyping of a single human. *Nat. Commun.* **6**, 8885 (2015).

39. Victor, P. Questioning economic growth. *Nature* **468**, 370–371 (2010).

40. Bateman, I. J. & Mace, G. M. The natural capital framework for sustainably efficient and equitable decision making. *Nat. Sustain.* (2020) doi:10.1038/s41893-020-0552-3.

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Author contributions: AL – formulated the main hypothesis, prepared the first draft of the UK Biobank data access application, preregistered the study, conducted analyses, interpreted results, produced initial draft of the manuscript; CA – was closely involved in results interpretations and discussions, proposed a number of supplementary analyses, contributed in drafting; KA – replicated main results, contributed in creating figures, took part in discussions and results interpretations, contributed in manuscript drafting; MI – was closely involved in results interpretation and discussions, proposed several important analyses, drafted the manuscript. PP – acquired funding, was closely involved in hypotheses submissions and preparations of the UK Biobank application, preregistration, proposed a number of important secondary and supplementary analyses, played key roles in results interpretation and discussions. All authors intellectually contributed to the study and took active parts in drafting and manuscript preparations, and approved the final draft of the manuscript.

Competing interests: Authors declare no competing interests.

Data and materials availability:

The access to the UK Biobank data was granted to the authors after submitting project description with stated hypotheses and analysis plan. The study was preregistered at the Open Science Foundation Framework database (https://osf.io/h52gk) prior to data transfer.

UK Biobank remains the owner of the database and accepts data request from third parties after approving corresponding project proposals and payments of the data access fees (more details: https://www.ukbiobank.ac.uk/principles-of-access).

Similarly, Parkinson's Progression Markers Initiative MRI data used to replicate the main findings is not publicly open, but can be accessed after completing a corresponding registration form (https://www.ppmi-info.org).

All scripts used in the main data analyses will be made publicly available at the corresponding author's GitHub page.