Title: Stock market fluctuations impact the emotional brain on a population level

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Summary:

Previous research suggests that market and population well-being are related [1–7]. However, the underlying mechanisms remain unclear. Using UK-biobank data we confirmed a significant association between a local stock market index (FTSE100) and mood of 479,791 subjects, and demonstrated that FTSE100 exhibits significant association with volumetric measures of the brain regions involved in affective processing in 39,755 subjects. Market decline (lower index scores) was associated with larger volumes of amygdala, nucleus accumbens, and orbitofrontal cortex, whereas insula and cingulate cortex exhibited opposite relationship. The effects were particularly strong in lowest- and highest-income citizens. More distant markets had a weaker relation to these regions. Toda-Yamamoto Granger causality tests [8] indicated that the direct market-brain path is stronger than the opposite. Our findings suggest how global events impact the population brain encouraging sustainable and well-being-oriented economic decision-making [9,10].

The study was preregistered in The Open Science Framework Registry (https://osf.io/h52gk).

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 [11], and the well-being of individuals who have no direct involvement in the stock market [1]. Moreover, it has been suggested that stock market turbulence increases anxiety [2], self-harm and suicide rates [3–5] and leads to an elevated number of fatal car accidents [6]. These effects may be particularly pronounced in long-lasting financial crises, as the 2008 stock market crash or the economy slowing in the COVID19 pandemic.

To date, there are no studies that have investigated the impact of market behaviour on 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 [12]. Similarly, an upcoming study also suggests that intense experience of the COVID19 outbreak is associated with a volumetric increase of the amygdala [13].

The present study aims to understand whether more subtle but frequently occurring global events leave a trace in the human brain on a population level. Here, we investigated how day-to-day fluctuations in the stock market impacts brain structure. Our approach innovates the field in multiple ways. First, instead of a one-time aversive event [12,13], we focused on daily fluctuations of negative and positive information reflecting the market. Second, instead of an experimental group, we studied a large sample of the UK population under naturalistic conditions. Thereby, our design is a naturalistic investigation of brain alterations when the population is exposed to a fluctuating flow of emotionally salient information encompassing rewards and losses.

To do this, we accessed structural MRI data of 39,755 UK citizens from the UK Biobank acquired over approximately 4.5 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**). 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 [14–17]: 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 [18–21].

Previous research suggests that brain morphometry is capable of capturing plastic changes that happen after weeks [22] or days [23] of engagement of the relevant brain networks. Moreover, even acute activation of brain networks is associated with morphometric alterations [24]. 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 [25].

Prior to the main analysis, we attempted to replicate previous behavioural findings suggesting a relation of market fluctuations with mood and well-being [1,4,7,26] on a large sample from the UK Biobank data (n = 479,791) collected over a period of 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 4.5-years of the MRI subsample (**Supplement Table S2**).

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

	β_{std}	*T(df)*	p_{fdr}
Negative Emotions (total)	**-0.03**	**-21.14(37671)**	**<0.001**
Irritability	-0.007	-4.31(37671)	<0.001
Sensitivity/hurt feelings	-0.04	-23.91(37671)	<0.001
Nervous feelings	-0.02	-10.93(37671)	<0.001
Worrier/anxious feelings	-0.02	-12.32(37671)	<0.001
Happiness	**0.05**	**21.17(15633)**	**<0.001**

β_{std} *- standardized* β *coefficients,* p_{fdr} *– p-values corrected for multiple testing with false discovery rate.*

We then tested and confirmed our main hypothesis by showing that FTSE100 was associated with significant structural changes in circuits processing rewards and losses. The most notable result was that bilateral amygdala, involved in threat detection and anxiety processing [17–21], showed a negative relation with the UK economic performance (**Fig. 1 and 2, Table 2,** whole-brain analysis is reported in **Supplement Fig. S2**).

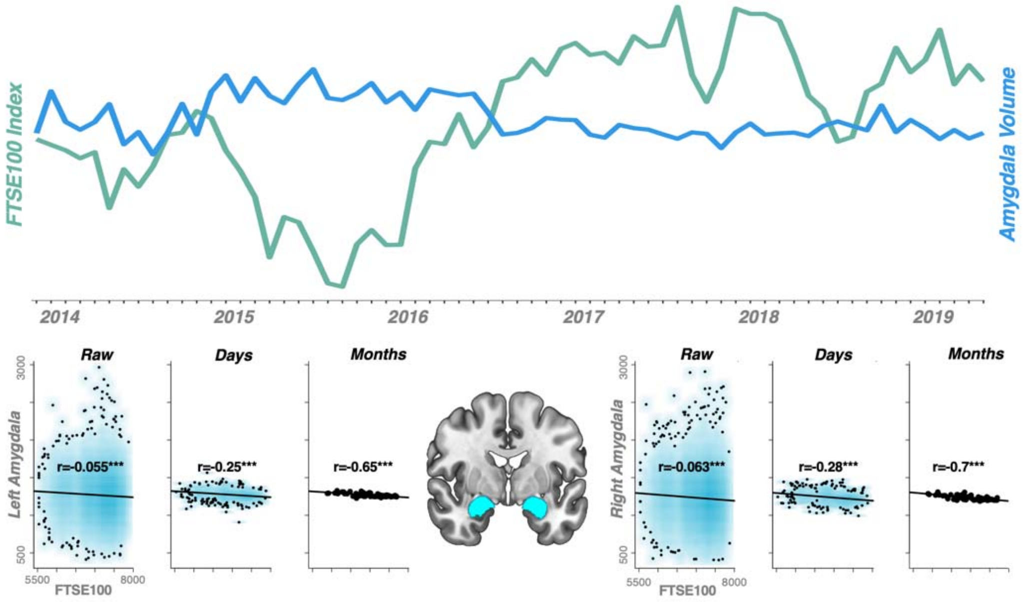

Fig.1** Studied brain-market associations. The figure illustrates the study rationale (top panel) and shows Pearson correlations (p<0.001) between FTSE100-index and amygdala volume (bottom panel).*

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

	Linear Mixed-Effects			**Effect-sizes, Pearson r (95% C.I.)**		
Region	β_{std}	T_{883}	p_{fdr}	***Raw***	***DayAVG***	***MonthAVG***
L Amygdala	-0.054	-9.51	<0.001	-0.055(-0.066,-0.043)	-0.253(-0.304,-0.202)	-0.65(-0.771,-0.484)
R Amygdala	-0.062	-10.91	<0.001	-0.063(-0.074,-0.052)	-0.282(-0.332,-0.231)	-0.697(-0.804,-0.548)
L Accumbens	-0.054	-9.54	<0.001	-0.055(-0.066,-0.044)	-0.232(-0.283,-0.18)	-0.67(-0.785,-0.511)
R Accumbens	-0.061	-10.89	<0.001	-0.064(-0.075,-0.052)	-0.259(-0.309,-0.207)	-0.73(-0.826,-0.592)
L LOFC	-0.026	-4.68	<0.001	-0.031(-0.042,-0.02)	-0.14(-0.193,-0.086)	-0.492(-0.656,-0.284)
R LOFC	-0.019	-3.49	0.001	-0.023(-0.034,-0.012)	-0.082(-0.136,-0.028)	-0.331(-0.53,-0.097)
L Insula	0.037	6.62	<0.001	0.042(0.031,0.053)	0.21(0.158,0.262)	0.494(0.286,0.657)

R Insula	0.0329	5.86	<0.001	0.037(0.026,0.048)	0.186(0.133,0.238)	0.443(0.226,0.619)
L Subcallosal	0.0178	3.18	0.002	0.021(0.009,0.032)	0.134(0.08,0.187)	0.363(0.133,0.556)
R Subcallosal	0.0153	2.74	0.008	0.019(0.007,0.03)	0.128(0.074,0.181)	0.358(0.127,0.552)
L Anterior Cingulate	0.0254	4.67	<0.001	0.035(0.024,0.046)	0.177(0.124,0.229)	0.492(0.284,0.656)
R Anterior Cingulate	0.024	4.44	<0.001	0.033(0.022,0.044)	0.169(0.115,0.221)	0.515(0.312,0.673)
L Paracingulate	0.0044	0.8	0.426	0.001(-0.01,0.012)	0.043(-0.012,0.097)	0.09(-0.155,0.325)
R Paracingulate	0.0046	0.83	0.426	0.003(-0.008,0.014)	0.051(-0.003,0.105)	0.139(-0.107,0.368)
Intracranial Volume	0.01	0.91	0.418	-0.009(-0.02,0.002)	-0.017(-0.071,0.038)	-0.107(-0.34,0.139)

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*

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 [12] and with the COVID19 pandemic experience on amygdala volume [13]. Together these results show that effects of global events are profound enough to affect threat- and fear circuits on a population level. Similar findings were observed for nucleus accumbens and lateral orbitofrontal cortex (lOFC) (**Fig. 2**, **A** and **B**).

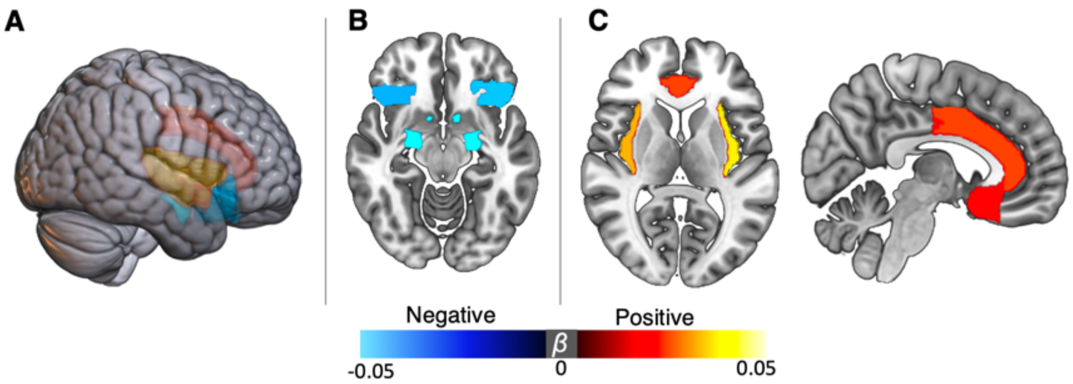

Fig. 2 *Regional profile of brain-market associations.*
A – three-dimensional view of the significant findings ($p_{FDR}<0.05$*). FTSE100 exhibited negative (B) associations with amygdala, nucleus accumbens and orbitofrontal cortex, whereas insular and cingulate regions were positively (C) associated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

While nucleus accumbens is mostly known for being involved in reward anticipation, it is equally important for processing losses [14,15]. lOFC has been suggested to be involved in processing expectations within the emotional domain [27–29], including losses and rewards [30,31]. 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 above, except for lOFC, are involved in both positive and negative emotional processes [14–16]. 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 to be more sensitive to positive outcomes in relation to stock market fluctuations. 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 FTSE 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. S2, Table S6**). These analyses suggest that the observed effects reflect predominantly, but not exclusively, mid-to-long-term plastic brain changes [22].

We amended the preregistered protocol to add 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), intracranial volume, as well a reference index Nikkei225 (**Supplement Table S3**). The Nikkei225 index is of particular interest as it represents the performance of a reference country with a similar size, sociodemographic characteristics, substantial connections to the global market and particularly strong economic ties with the UK. Further, the FTSE100 and Nikkei225 correlate strongly (r=0.83). Thus, the fact that the finding remains after adjusting for the Nikkei225 implies that the local economic performance captured by the FTSE100 is a stronger contributor to emotional and biological characteristics of the citizens than the global stock market.

A similar pattern of associations as the one for FTSE100 was observed for the equivalent local European indexes (German GDAXI and French MIB.MI) 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 Chinese WisdomTree ICBCCS S&P 500 Fund (WCHN) and the Shanghai Composite Index (SSEC).

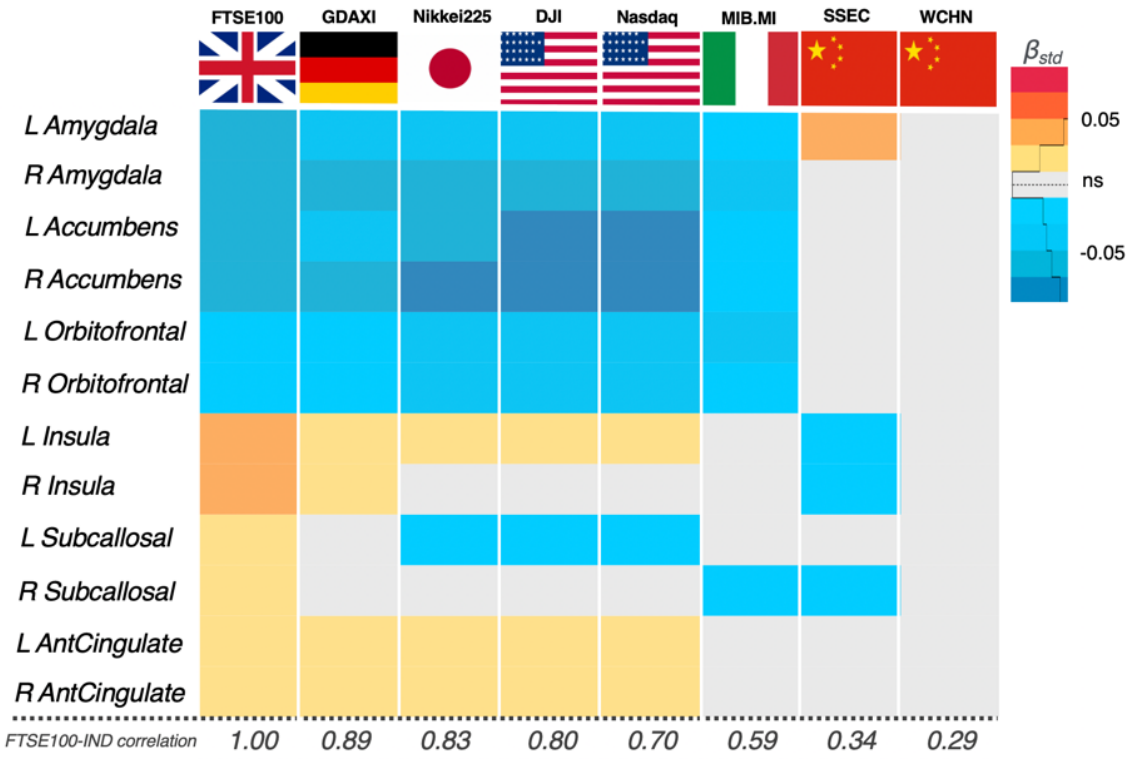

***Fig. 3** Pattern of brain-market associations for different capital market indexes.*
Strongest associations were found for the UK market index (FTSE100). American and Japanese indexes also exhibited substantial effects on grey matter volumes of UK citizens possibly due to strong economic ties with Great Britain. Other European indexes exhibited similar but substantially weaker pattern of associations, whereas the Chinese indexes had weak-to-none associations with the studied volumetric measures. FTSE100-IND correlations: Pearson correlation of FTSE100 with other investigated indexes.

We also performed an exploratory analysis using the VIX volatility index characterizing global capital market turbulence and observed a reversed pattern of associations in the insula and cingulate regions (**Supplement Table S4**). Thus, not only decreases in stock market performance but also economic insecurity seems to be associated with changes in the affective brain circuits.

All of the main analyses (**Fig. 2-3**, **Tables 1-2**) leveraged random linear mixed effects framework with subject as a random effect, as a subset (n=1427) of the study subjects was scanned twice.

Conceptually, 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 [1,3,7]. These effects, heavily reinforced by media, represent threat signals and subsequently impact brains and emotional states of the population. 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 [32,33]. 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 would suggest that the changes in the mood of the population and relevant brain networks would impact the market. This hypothesis is partially in line with the data acquired in small-scale experimental studies demonstrating involvement of reward and fear circuits in future financial decisions [34–36].

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 is present in the stock market time-series (**Supplement Table S7**), the fact that earlier economic data peaks with the brain volume implies that the market events are 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 and also for the mood data with the FTSE100, but no clear antecedent relationship can be drawn (**Supplement Fig. S3 and S4**).

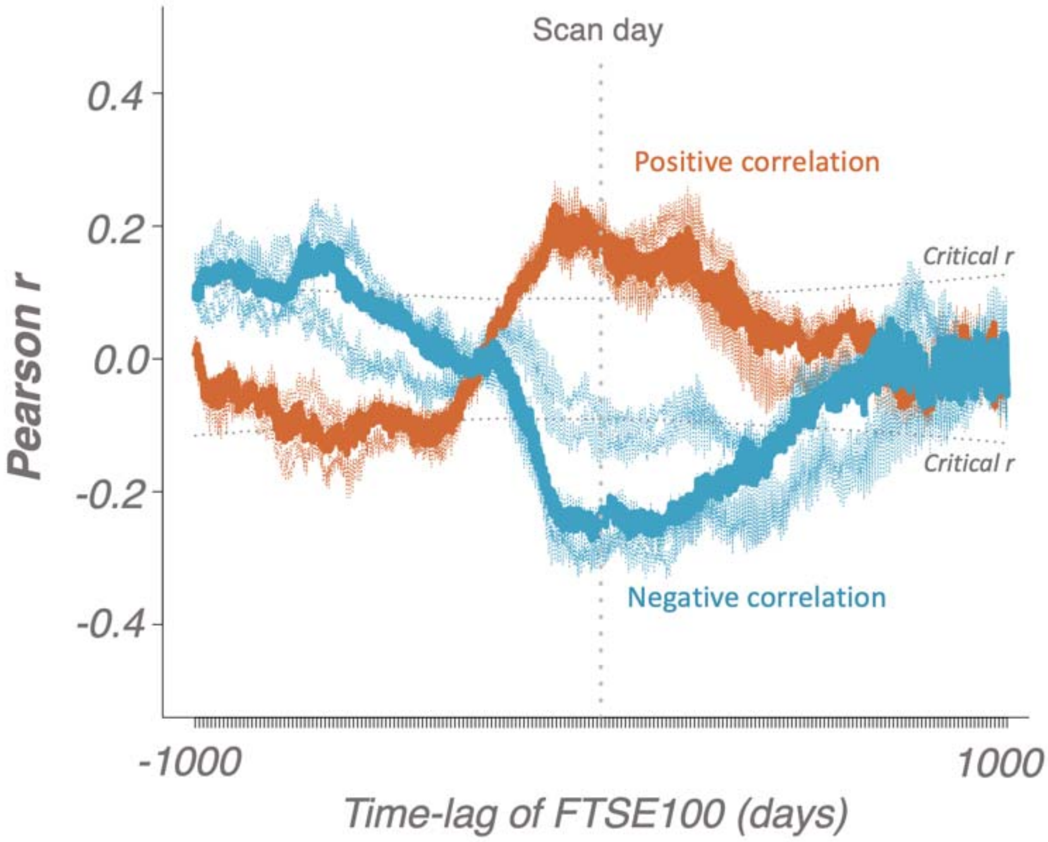

Fig. 4 *Pearson correlations for the brain and FTSE100-lagged data averaged over days. Transparent lines represent individual regions whereas thick lines represent medians of the correlations. Dotted boundaries represent critical r-values for α=0.001. The plot represents magnitudes of associations between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

In order to further quantify the directional relationship and contrast the two alternative explanations against each other we applied Toda-Yamamoto implementation of Granger Causality tests for all of the regions (n=12) that showed significant association with the market outcome (**Table 2**). For most of the investigated morphometric measures, hypothesis "Market impacts Population Brain" was more supported by the data (**Table 3**). Nevertheless, the hypothesis "Population Brain impacts Market" was also supported with larger time-lags for amygdala and subcallosal cortex. Thus, our result suggesting that the "market impacts well-being" is in line with previous Granger causality analyses of the global and more indirect measures of well-being [7]. However, a bidirectional link cannot be fully ruled out, since the opposite, albeit weaker, causal link may also exist [32,33].

Table 3. *Causal relationships between the studied brain variables and market oscillations (daily scale).*

	H1: "Population Brain impacts Market"	***H2: "Market impacts Population Brain"***	***Portmanteau Stability Test***
L Amygdala	χ^2(df)=21.72(5), p=0.001	χ^2(df)=16.92(5), p=0.005	L=5, χ^2(df)=50.44(44), p=0.234
R Amygdala	χ^2(df)=26.5(13), p=0.015	χ^2(df)=87.39(13), p<0.001	L=13, χ^2(df)=13.98(12), p=0.302
L Accumbens	χ^2(df)=0.43(1), p=0.512	χ^2(df)=0.18(1), p=0.672	L=1, χ^2(df)=63.65(60), p=0.349
R Accumbens	χ^2(df)=0.13(1), p=0.718	χ^2(df)=6.49(1), p=0.011	L=1, χ^2(df)=72.39(60), p=0.131
L LOFC	χ^2(df)=0.5(1), p=0.481	χ^2(df)=4.69(1), p=0.03	L=1, χ^2(df)=60.35(60), p=0.463
R LOFC	χ^2(df)=0(1), p=0.996	χ^2(df)=2.56(1), p=0.11	L=1, χ^2(df)=65.54(60), p=0.291
L Insula	χ^2(df)=13.57(11), p=0.258	χ^2(df)=75.03(11), p<0.001	L=11, χ^2(df)=20.86(20), p=0.406
R Insula	χ^2(df)=13.65(11), p=0.253	χ^2(df)=95.14(11), p<0.001	L=11, χ^2(df)=25.92(20), p=0.168
L Subcallosal	χ^2(df)=18.82(8), p=0.016	χ^2(df)=75.06(8), p<0.001	L=8, χ^2(df)=36.65(32), p=0.262
R Subcallosal	χ^2(df)=16.54(8), p=0.035	χ^2(df)=84.08(8), p<0.001	L=8, χ^2(df)=37.55(32), p=0.23
L Anterior Cingulate	χ^2(df)=7.19(5), p=0.207	χ^2(df)=29.54(5), p<0.001	L=5, χ^2(df)=61.26(44), p=0.043
R Anterior Cingulate	χ^2(df)=0.05(1), p=0.829	χ^2(df)=2.81(1), p=0.093	L=1, χ^2(df)=116.67(60), p<0.001

For all the regions that passed the Portmanteau stability test for residual serial correlation (highlighted in bold), hypothesis 2 (H2: "Market impacts Polulation Brain") received more support (underlined) compared to hypothesis 1 (H2: "Population Brain impacts Market") with the optimal lag length (L) according to AIC criterion. However, H1 was also supported for amygdala and subcallosal cortex.

Our study confirmed that stock market moves and well-being of the population are related and for the first time demonstrated that the economic performance of a country impacts the brains of its citizens in a profound and lasting way. These effects may have a large influence on a population level and may, in turn, lead to cascading changes in the collective dynamics, further influencing the society at large. 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 [9,10].

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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 clearly 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).

All scripts used in the main data analyses will be made publicly available at AL’s GitHub page: https://github.com/alex-lebedev.