Physiological stress, sustained attention, emotion regulation and cognitive engagement in 12-month-old infants from urban environments.

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Abstract

The past two centuries have seen a rapid increase in the proportion of children who grow up in cities. However, relatively little work has explored in detail the physiological and cognitive pathways through which city life may affect early development. To assess this, we observed a cohort of infants growing up in diverse settings across the South-East UK across a two-day assessment battery. On visit 1, day-long home recordings were made to monitor infants' physiological stress in real-world settings. On visit 2, lab batteries were administered to measure infants' cognitive, emotional and neural reactivity. Infants from more high density urban environments showed increased physiological stress (decreased parasympathetic nervous system activity) at home. This relationship was independent of socio-economic status and lifelong stressors. Behaviourally, infants raised in high-density settings showed lower sustained attention in the lab, along with increased behavioural and physiological reactivity during an emotion elicitation task. However, they also showed increased recognition memory for briefly presented stimuli and increased neural engagement with novel stimuli. This pattern is consistent with other research into how elevated physiological stress influences cognition, and with theoretical approaches from adult research that predict that city life is associated with a profile of cognitive strengths as well as weaknesses. Implications for education and developmental psychopathology are discussed.

Keywords: urban environment, attention, emotional reactivity, infancy, learning

Introduction

200 years ago, 7% of the world's children were born in cities, compared to over 55% today¹. By 2050, this number is expected to reach about 70% (UNICEF, 2019). Although many physical health outcomes are superior in city dwellers (Hartley, 2004), research into the cognitive effects of city life has mainly documented negative effects in older children (Evans, 2006). Even when other socioeconomic factors are controlled for, teenagers living in high density environments show higher rates of psychosomatic illness, poorer cognitive control, and higher levels of directed attention fatigue (Obasanjo, 1999, Richman, 1977). Studies have noted that effects are generally moderated by age, such that younger individuals are more profoundly affected (Wells, 2000). By adulthood, exposure to the urban environment associates with altered neural stress processing (affecting the amygdala and anterior cingulate cortex) (Lederbogen et al., 2011) and with worse attention control and increased distractibility (e.g. increased distractor interference on a flanker selection task) (Linnell, Caparos, de Fockert, & Davidoff, 2013, Berman, Jonides, & Kaplan, 2008).

However, other research has suggested that city life may, by adulthood, be associated with a profile that includes cognitive strengths, as well as weaknesses (Linnell & Caparos, 2020). This builds on research into the complex ways in which increased physiological stress (which has repeatedly shown to be higher in urban environments) affects cognition (Arnsten, 2009). In animals, elevated stress associates with impaired selective attention (Minor, Jackson, & Maier, 1984), and a perseverative pattern of responses consistent with prefrontal cortex dysfunction (Arnsten & Goldman-Rakic, 1998). In adults, exposure to psychosocial stress leads to worse performance on attentional set-shifting, and concomitant decreases in fronto-parietal connectivity (Liston, McEwen, & Casey, 2009). These changes are mediated by

¹ <https://data.worldbank.org/indicator/sp.urb.totl.in.zs>

catecholamines such as dopamine and norepinephrine, released during stress by brainstem sympathetic nuclei (Joëls & Baram, 2009). But while stress downregulates the frontal lobes, it simultaneously enhances processes dependent on subcortical structures (Luethi, Meier, & Sandi, 2009), increases signal-to-noise ratios within primary sensory cortices (Foote, Freedman, & Oliver, 1975) and leads to more vigilant or bottom-up, stimulus-driven, attention (Buschman & Miller, 2007). These changes are thought to be adaptive insofar as downregulated frontal activity and upregulated subcortical activity during periods of acute stress allows animals to more rapidly ascertain potential risks and respond to uncertainties in the environment with learned or pre-potent actions (Aston-Jones & Cohen, 2005; Dayan & Yu, 2003). Consistent with this, previous research examining a cohort of small-town dwelling infants has shown that infants with elevated physiological stress show both reduced visual sustained attention, and superior recognition memory for briefly presented images (de Barbaro, Clackson, & Wass, 2016b).

No previous research has examined how high density urban environments affect early development, during infancy. Understanding this can elucidate whether the relationships previously documented in older children are mediated by more long-term cognitive factors such as learnt helplessness (Wells, 2000), in which case they ought not to be observed in infants, or whether they arise as a result of environmental factors that are also prevalent during early life. [...] Understanding these developmental pathways is also important because individuals are considered most phenotypically sensitive to environmental influences during early life (Bryck & Fisher, 2012) – and so it is possible that the effects of urban living on development are stronger during infancy than at other times.

To address these questions, we recruited a cohort of 12-month-old infants from diverse

backgrounds across the South-East of the UK, which is an area showing both high- and low-density living environments (see SM Figure S1). Participating infants attended two sessions: at the first, infants wore miniaturised microphones and cameras, along with physiological stress monitors (electro-cardiogram, actigraphy) to provide a day-long recording of physiological stress in home settings (see Figure 1). Participating infants also attended a lab testing battery.

First, we examined the association between housing density and physiological stress levels, in infants while they were at home (Analysis 1). Stress was operationalised by calculating Respiratory Sinus Arrhythmia (RSA), a measure of heart rate variability which is thought to measure activity within the parasympathetic nervous system (Anrep, Pascual, & Rossler, 1935) (higher RSA indexing higher parasympathetic nervous system activity, and lower overall physiological stress). We recorded, and controlled for, socio-demographic influences in our sample by measuring maternal education, household income and the number of adverse/stressful life events to which participants had been exposed. Based on previous results into the physiological effects of urban environments on older children (Evans, Lercher, Meis, Ising, & Kofler, 2001) we predicted that infants raised in higher density (HD) urban environments would show elevated physiological stress, and that these relationships would exist even after other factors were controlled for.

We also examined how early exposure to urban environments impacts cognitive performance across different components on the lab testing battery (Analysis 2). Our testing battery was designed to assess whether the same pattern as observed in adult research – that individuals from HD environments show both strengths, and weaknesses, relative to individuals from lower density (LD) environments – was also observed during early life. Therefore, we assessed infants' capacity to sustain attention towards an engaging target for an extended period of time

(Brandes-Aitken, Braren, Swingler, Voegtline, & Blair, 2019; Razza, Martin, & Brooks-Gunn, 2010), and infants' emotion reactivity to a mild stressor by administering the still face procedure (Weinberg & Tronick, 1996). Based on previous research (Arnsten, 2009; de Barbaro et al., 2016b; Wass, Smith, Daubney, et al., 2019) we predicted that HD infants would show reduced sustained attention and increased emotion reactivity to a stressor.

In addition, we also administered two measures of rapid learning and engagement, that we predicted may be elevated in the HD group. Specifically, we tested infants' ability to recognise previously presented objects following a short delay (recognition memory) (Rose, Feldman, & Jankowski, 2012). And we measured brain activity, concentrating on theta band activity. Theta band activity is widely used as an index of attention engagement and learning (Wass, Noreika, et al., 2018; Wass et al., pre-print Berger, Tzur, & Posner, 2006 Begus & Bonawitz, 2020; Begus, Gliga, & Southgate, 2016; Begus, Southgate, & Gliga, 2015; Jones et al., 2020). Importantly, theta power *differentiates* between active attentional engagement and sustained attention (defined as simply maintaining attention towards a stimulus for sustained periods of time) (see Richards, 2010; Ruff & Capozzoli, 2003; Ruff & Rothbart, 1996 for behavioural and physiological work examining this distinction). For example, Orekhova and colleagues found higher theta power in 8-month-old infants during internally controlled *when compared with* externally controlled attention (Orekhova, Stroganova, & Posikera, 1999); Xie and Richards observed elevated theta power over frontal pole, temporal and parietal electrodes during heart-rate defined sustained attention, *when compared with* looking in the absence of accompanying heart rate changes (Xie, Mallin, & Richards, 2018; see also Richards, 2011); and Jones and colleagues found that non-social videos elicited more visual attention than social videos in 6- and 12-month-old infants, but that theta power was selectively enhanced only to social videos (Jones, Venema, Lowy, Earl, & Webb, 2015). Although relationships between

attention and alpha desynchronization have also been noted, these tend to be more mixed and inconsistent (Bell, 2002; Orekhova, Stroganova, & Posikera, 2001; Stroganova, Orekhova, & Posikera, 1999; Xie et al., 2018; Wass, Noreika, et al., 2018) meriting our decision to concentrate on theta in this study. Based on previous research suggesting that rapid learning and attentional engagement are heightened in urban-dwelling adults (Linnell & Caparos, 2020) and in infants with higher physiological stress (de Barbaro et al., 2016b) we predicted that HD infants would show superior visual recognition memory and increased theta power towards novel stimuli.

Finally, and although it was (regrettably) beyond the scope of this paper fully to explore the diverse factors that might mediate any observed relationships between HD living, physiological stress and cognitive performance, we also took advantage of our study design to explore how the following environmental factors differed between HD and LD infants: noise exposure, proportion of time spent at home vs not at home, and movement levels while outdoors (as a proxy for whether infants were allowed to roam freely while outdoors, or strapped into a pushchair or buggy) (Analysis 3). We had no specific hypotheses for this final, exploratory component of the study, as (to our knowledge) no previous studies have examined how HD and LD infants differ on these variables during early life.

Materials and Methods

The study was approved by the ethics board at XXXX.

Participants

Participants were recruited by researchers visiting infant-parent groups, both privately organised and through local councils, as well as by mail by purchasing names and addresses of families in specific income brackets and areas of the UK. No specific attempts were made to ensure that all income brackets were equally well represented in high-density and low-density groups.

Exclusion criteria were: complex medical conditions, skin allergies, heart conditions, parents below 18 years of age, and parents receiving care from a mental health organisation or professional. We also excluded families in which the primary day-time care was performed by a male parent, because the numbers were insufficient to provide an adequately gender-matched sample.

Usable data from all three components of the study - the questionnaires, lab visit and home visit - were obtained from 57 infants recruited from the London, Essex, and Hertfordshire regions of the UK (henceforth referred to as 'Main sample'). Usable data from two components of the study - the questionnaires and home visit - were obtained from 82 infants following the inclusion of an additional cohort from the Cambridgeshire region (henceforth referred to as 'Expanded sample'). Maps showing the approximate living locations of all participants and details of the building types in which they lived are given in the SM (section 1.1).

Demographic details for the main (N=57) sample are given in Table 1; those for the expanded (N=82) sample are given in Table S1. Coding of parental employment was conducted using the Socio-Economic Classification scheme from the UK Office of National Statistics (2001)². Stressful events around the birth were defined as: medical complications, preterm birth, drink or drugs while pregnant or previous miscarriage. Adverse events around the birth were defined as: serious illness, death in family, abuse/attacks/threats to family, unemployment in family, financial difficulties, committing or being victim of a crime, moving house; both measures were coded as summative scales. All measures were elicited via parent report.

Participants' housing density was calculated based on home post code data that they supplied. This was converted into 'Number of persons per hectare' at their home living address using data available at <http://datashine.org.uk/>⁴. For some of the time-series analyses presented in the results section, we also conducted a median group split by housing density. The mean (*std*) (*range*) of housing density (in people/hectare) was 51.6 (33.4) (1-108) for the low density group and 235.8 (210) (111-1570) for the high density group.

Of note, previous analyses based on different aspects of these data, that address different research questions using different analyses, have been published before (Wass, Smith, Clackson, & Mirza, 2020; Wass, Smith, Clackson, et al., 2019; Wass, Smith, Daubney, et al., 2019).

INSERT TABLE 1 HERE

2

<https://www.ons.gov.uk/methodology/classificationsandstandards/otherclassifications/thenationalstatisticssocioeconomicclassificationnssecrebasedonsoc2010>

³ <https://www.datashine.org.uk> OAC Variables/Variable 7

⁴ <https://www.datashine.org.uk> OAC Variables/Variable 7

Equipment and procedures

Home visit

Protocol. The lab and home testing sessions were scheduled within median (*st err*) 17.5 (3.5) days of the one another. For the home visit, parents selected a day for which they would be spending the entire day with their child but that was otherwise, as far as possible, typical. The researcher visited the participants' homes in the morning (between 7.30 and 10am) to fit the equipment and explain its use, and then returned in the late afternoon (between 4 and 7pm) to remove it. Mean (*std*) recording time per day was 7.3 (1.4) hours. Participants generally reported no discomfort and disruption to their normal routines from wearing the equipment.

Equipment. The equipment consisted of two wearable layers (see Figure 1). A specially designed baby-grow was worn next to the skin, containing a built-in Electro-Cardiogram (ECG) recording device (recording at 250Hz), accelerometer (30Hz), GPS (1Hz), and microphone (11.6kHz). A T-shirt, worn on top of the device, contained a pocket to hold the microphone and a miniature video camera (a commercially available Narrative Clip 2). The clothes were comfortable when worn and, other than a request to keep the equipment dry, participants could behave exactly as they would on a normal day. No discomfort in wearing the equipment was generally reported. To ensure good quality recordings, the ECG was attached using standard Ag-Cl electrodes, placed in a modified lead II position.

During the home visit, the mothers of all research participants also took part in ECG recording. This used the same 3-lead set-up with standard Ag-Cl electrodes, placed in a modified lead II position. The ECG recording device was stored in a small box held in place via a strap worn under the clothing.

INSERT FIGURE 1 HERE

Electro-Cardiography Data processing. ECG data were parsed to identify RR intervals using custom-built Matlab scripts, employing an adaptation of a standard thresholding procedure (Wass, de Barbaro, & Clackson, 2015), and verified *post hoc* via visual inspection. Heart Rate Variability was calculated using the PhysioNet Cardiovascular Signal Toolbox (Vest et al., 2018). A 60-second window with an increment of 60 seconds was implemented, and the default settings were used with the exception that the min/max inter-beat interval was set at 300/750 ms for the infant data and 300/1300 ms for the adult data. The Root Mean Square of Successive Differences (RMSSD) measure was taken to index Respiratory Sinus Arrhythmia (RSA) (Vest et al., 2018), but other results based on frequency domain measures are also presented in the SM (section 3.1).

Actigraphy data processing. To parse the actigraphy data the data were first manually inspected, then corrected for artifacts specific to the recording device used. Following that, a Butterworth low-pass filter with a cut-off of 0.1 Hz to remove high-frequency noise.

Microphone data processing. Microphone data were recorded at 11.56 kHz, and converted to decibel values using the `mag2db` function in MATLAB. For reasons of recording bandwidth, the microphone did not record continuously, but recorded a 5-second snapshot of the auditory environment every 60 seconds throughout the day.

Home/not home coding. Identification of when participants were at home was performed using the GPS monitors built into the recording devices. The position of the participant's home was calculated based on the postcode data that they supplied, and any GPS samples within a 50m area of that location were treated as Home (corresponding to the accuracy of the GPS devices that we were using).

Awake/asleep coding. To identify samples in which infants were sleeping, parents were asked to fill in a logbook identifying the times of infants' naps during the day. This information was manually verified by visually examining the actigraphy and ECG data collected, on a participant by participant basis. Actigraphy, in particular, shows marked differences between sleeping and waking samples, which allowed us to verify the parental reports with a high degree of accuracy. N=4 of the participants recorded did not sleep during the day that we were recording.

INSERT FIGURE 2 HERE

Lab visit

Eyetracking recording. A Tobii T120 eyetracker (Tobii AG, Stockholm) was used for tests 1 and 2. Stimuli were presented using custom-built scripts using Matlab and Psychtoolbox, interfacing with the eyetracker via the Matlab Tobii SDK.

ECG recording. For the lab visit, ECG was recorded using Bionomadix BN-ECG2 and BM-ACCL3 units, along with an MP160 amp, from Biopac (Santa Barbara, CA) system recording at 1000Hz. ECG was recorded using disposable Ag–Cl electrodes placed in a modified lead II position.

EEG recording. EEG was recorded using a high-density 128-channel HydroCel Geodesic Sensor Net (HGSN) produced by EGI (EGI, Eugene, OR). The size of the HGSN was chosen based on the child's head circumference. The EEG signal was recorded to a vertex reference, at a 500 Hz sampling rate with band-pass filters set from 0.1–100 Hz using a Kaiser Finite Impulse Response filter. Prior to recording the impedance of each electrode was manually checked to ensure that they were below 50 k Ω m.

Experimental protocols for lab visit

Test 1: Visual recognition memory

Three blocks were presented of the visual recognition memory task, interspersed with the other elements of the testing battery in a pseudorandomised order. Each block consisted of two parts: a familiarisation phase, and a test phase.

Familiarisation phase: In each block, a previously unseen still image was presented, subtending 7°, consisting of a child's face against a white background (e.g., see Figure 2f). The image was presented in silence. An experimenter, watching a live video feed of the child from behind a curtain, coded whether they were looking at the screen using a key press. When the child had looked away for 1 s or more, this marked the end of the trial. The same image was then presented again. A running count of the longest look obtained so far that block was recorded, and updated after each trial. The same image was presented until the child had completed two consecutive looks at less than 50% of the longest look that block (Colombo & Mitchell, 2009). If the child had not met this criterion within 12 trials or within 120 s of accumulated looking time, the experiment was aborted and the block was excluded. Between

trials, a re-fixation target was presented, to ensure that the infant was looking at the screen at the start of each trial.

Test phase: Immediately following the familiarisation phase, the previously familiarised image was presented concurrently with a novel image—each subtending 7° (see Figure 2f). The images were presented in one Left-Right order for 8,000 ms, and then the order was swapped for the subsequent 8,000 ms (Rose, Feldman, & Jankowski, 2012), while infants' gaze behaviour was tracked. The dependent variable was the proportion of time spent looking to the novel image during the test phase. Piloting work ensured that the pairs of stimuli used were of equal salience.

Eyetracker data processing. To parse the data from the test phase, binocular eyetracking data were averaged to monocular data, and smoothed using a continuous 150cms moving window. To minimise the effect of data drop-out due to variable quality tracking (Wass, Forssman, & Leppanen, 2014), proportion looking to the novel target was calculated as time spent viewing the unfamiliar target, divided by the time spent viewing both the familiar and the unfamiliar target combined. Due to non-compliance during testing, no usable data from this task were collected from N=7 participants.

Of note, previous research has shown that performance on this task, in which recognition memory is tested immediately following the habituation period, shows strong associations with performance on an identical task in which recognition memory is tested following a longer delay (1/3/5 minutes) (Rose et al., 2012). Research has shown that performance on this task in infancy selectively predicts working memory performance assessed at 11 years using the CANTAB battery (Rose et al., 2012).

Test 2: Sustained attention.

In order to obtain as accurate as possible a measure of sustained attention (Wass, 2014) we assessed it in three contexts. First, we recorded infants' look duration during the familiarisation phase of the visual recognition memory task (described above), in which a static image of a child's face was presented repeatedly and children's looking behaviour was recorded. Second, the child's looking behaviour was assessed while a series of attractive age-appropriate dynamic videos was presented. Three blocks were presented; each block contained two 30-40-second videos. The dependent variable was the duration of infants' looks to the screen. Third, we assessed sustained attention under conditions of distraction by recording the child's looking behaviour while presenting a static target (a cartoon butterfly) concurrently with moving distractors in the child's peripheral visual field (cartoon clouds, trees flowers, etc) (see Rose, Wass, Jankowski, Feldman, & Djukic, 2017 for further details). The dependent variable was the child's ability to sustain their attention to the static target, indexed by the proportion of time spent looking to the target relative to the distractors. Three blocks were presented of four trials per block.

Although previous research has suggested that infants' looking to static and dynamic stimuli taps into putatively different underlying attention mechanisms (Courage, Reynolds, & Richards, 2006), we in fact observed positive associations between looking durations to all stimuli at this age (12 months), consistent with previous findings (Wass, 2014). The composite measure was calculated by calculating the z-score on a per-task, per-participant basis and averaging the z-scores. In total, data for the sustained attention composite measure were unavailable for 2 participants.

ECG data processing. In addition to behaviour, we also assessed physiology (heart rate decelerations relative to the appearance of novel attention-eliciting stimuli), as previous research has indicated strong associations between physiology and behavioural measures of sustained attention in infancy, and suggested that physiology may be a better measure of sustained attention in some instances (Richards, 2010). To do this, heart rate data were parsed to identify RR intervals using the same procedure as described for the home visit ECG data, above. The data were then divided into 1-second epochs and z-scored separately for each participant. Group differences for time series analyses were calculated using the same permutation-based temporal clustering analysis as used for the EEG data (described below).

Test 3: Emotion regulation

The emotion regulation task was a standard version of the still face protocol (Weinberg & Tronick, 1996). Parent and child were seated across a 80cm-wide table, and instructed to play naturally with four toys positioned on the table. After four minutes, on an instruction from the experimenter, the parent was instructed not to respond to the infant and to hold a neutral face for two minutes. On a further instruction from the experimenter, the play resumed for a further two minutes. If the infant become distressed during the still face period, as judged using the standard guidelines (Weinberg & Tronick, 1996), the experiment was curtailed.

Video coding. Facial and vocal affect was coded in 5-second bins using a 7-point scale, where -3 is intense negative affect, 0 is neutral, and +3 is intense positive affect. To ascertain inter-rater reliability, 20% of the sample was double coded, and Cohen's Kappa was calculated. Inter-rater reliability was found to be 0.66, which is considered acceptable. Data for the facial affect coding were unavailable for three participants. To estimate change in facial affect during the still face protocol, a linear regression was plotted and the gradient of the line taken to index

the change in facial affect during the protocol. A median split analysis identified no difference in facial affect during the free play session immediately preceding the still face – mean (S.E.) $+0.06$ (0.02)/ $+0.05$ (0.03) for low/high density groups respectively across all epochs – suggesting that this approach is valid.

ECG data processing. ECG data were first parsed to identify RR intervals using the same procedure as described for the home visit data, above. Then, following the standard procedure (Ham & Tronick, 2009), change in heart rate during the still face episode was estimated by calculating the average heart rate during the still face episode and subtracting it from the average heart rate during the free play session immediately preceding the still face episode. Heart rate recovery was similarly estimated by calculating the average heart rate during the free play resumption and subtracting it from the average heart rate during the still face episode. Technical problems led to data being unavailable for a subset of participants (a faulty ECG cable (N=10); inaccurate synching (N=13) with the recording equipment for this procedure).

Test 4: EEG protocol.

Participants were presented with age-appropriate dynamic videos of the *CBeebies* television presenter Mr Tumble singing nursery rhymes. Three blocks were presented. Each block contained two videos totalling c. 80 seconds.

EEG data processing. Full details of the seven-stage artefact rejection procedure for the EEG data is given in the SM (section 1.2).

To calculate EEG spectral power following artefact rejection, a linear detrend was first applied, for each channel and for each epoch, and then an FFT was carried out using the built-in function

in Matlab (Mathworks Inc). The FFT was performed on data in 2000 ms epochs, which were segmented with an 87.5 % (1750 ms) overlap between two adjacent epochs. The FFT was calculated in 1Hz frequency bins, examining frequencies between 1 and 16 Hz. For each epoch, the power at that bin was expressed as relative power – i.e. the total power at that frequency divided by the total power across all frequencies (1-16 Hz) at that epoch.

The behaviour of the child during the presentation of the stimuli was recorded, and videoed *post hoc* to identify periods during which the child was looking to the stimulus presentation area. The timings of looks to and away from the screen were identified to the nearest frame (30 fps, corresponding to 33ms per frame). Due to its labour-intensive nature, coding of the looking behaviour for this task was completed for a subset (65%) of participants, and only data from these participants has been included in the time series analyses. 20% of the sample was also double coded to assess inter-rater reliability. Cohen's Kappa was found to be 0.99, reflecting the high reliability of this coding.

Cross-correlation of EEG power with looking behaviour. The procedure used to calculate the cross-correlation between visual attention and EEG power was based on that used in previous research (de Barbaro, Clackson, & Wass, 2016a; Wass et al., in press). More details of the method used are given in these publications. The attention data used for the cross-correlation analysis was re-sampled as continuous and time-synchronised data-streams at 4Hz (to match that of the EEG power estimate). Attention data were coded as 1 and 0 (either attentive towards the play object, or not). Because previous research had identified a strong association between EEG power and visual attention that was limited to the 3-6Hz frequency range (see Figure 2 in Wass, Clackson, et al., 2018) the present analyses concentrated on this frequency band. For each computation, the zero-lag correlation was first calculated across all pairs of time-locked

(i.e. simultaneously occurring) epochs, comparing the EEG power profile with the attention data using a nonparametric (Spearman's) correlation. For comparison, we also calculated the results of the same tests repeated using alternative test, the Mann-Whitney U test, for which results were identical (results not shown here). The mean correlation value obtained was plotted as time "0" ($t=0$) in the cross-correlation. Next, time-lagged cross-correlations were computed at all lags from -10 to +10 seconds in lags of ± 250 ms (corresponding to one data point at 4 Hz). For example, at lag-time $t=-250$ ms, the EEG power profile was shifted one data point backwards relative to the attention data, and the mean correlation between all lagged pairs of data was calculated. In this way, we estimated how the association between two variables changed with increasing time-lags. The individual cross-correlation series was then averaged across participants to obtain the group mean cross-correlation at each time interval and frequency band.

Permutation-based temporal clustering analyses. To estimate the significance of the time-series results, a permutation-based temporal clustering approach was used. This procedure, which is adapted from approaches widely used in neuroimaging analyses (Maris, 2012; Maris & Oostenveld, 2007), allows us to estimate the probability of temporally contiguous relationships being observed in our results, a fact that standard approaches to correcting for multiple comparisons fail to account for (Maris & Oostenveld, 2007). See also Oakes, Baumgartner, Barrett, Messenger, & Luck, 2013 for a similar approach.

This analysis examines whether temporally contiguous patterns of change were observed in situations where the centre point of the expected response window is unknown (Maris & Oostenveld, 2007). In each case, the test statistic (e.g. in the case of Figure 2j, the between-samples t-test) was calculated independently for each 5-second epoch. Series of significant

effects across contiguous time windows were identified using an alpha level of .05. 1000 random datasets were then generated, the same sequence of analyses was repeated, and the longest series of significant effects across contiguous time windows was identified. The results obtained from the random datasets were used to generate a histogram, and the likelihood of observed results have been obtained by chance was calculated by comparing the observed values with the randomly generated values using a standard bootstrapping procedure. Thus, a p value of $<.01$ indicates that an equivalent pattern of temporally contiguous significant group differences was observed in 10 or fewer of the 1000 simulated datasets created.

Results

The results section is in three sections. Analysis 1 examines the association between housing density and physiological stress levels, in infants while they were at home. Analysis 2 examines the association between housing density and cognitive performance across different components of the lab testing battery. Analysis 3 examines how housing density associated with differences in at-home environmental factors.

Kolmogorov-Smirnov tests indicated that not all parameters were normally distributed, and so, for parsimony, more conservative non-parametric statistics are reported throughout.

Analysis 1 - association between housing density and physiological stress in infants at home.

Fig 2 a-d shows descriptive analyses of the heart rate data collected during the first 40 minutes of sleep from two participants; one shows low RSA (top row) and the other high RSA (bottom row). Although RSA is notoriously sensitive to movement artefact (Porges, 2007), we found nevertheless that RSA levels recorded between sleeping and waking samples showed high concordance ($q=.74$, $p<.001$). A significant negative relationship between waking RSA and housing density was observed ($q=-.34$, $p=.003$) (higher housing density associated with less RSA) along with a trend relationship between sleeping RSA and housing density ($q=-.20$, $p=.09$). No relationship was observed between housing density and overall movement levels ($q=.04$, $p=.74$). In the SM (section 2.1) we present additional analyses based on a calculation of RSA in the frequency domain. In the SM (section 2.2) we show how housing density varied by ethnicity.

Table 2 shows the bivariate correlations between infant RSA, other measures of socio-economic status, and life-time stressors in the expanded sample, and mother RSA. No relationship was noted between infant RSA and either the number of other children living in the household ($r=-.07$, $p=.48$). Figure 3 shows a break-down of infant RSA values subdivided by household income and maternal education.

INSERT TABLE 2 HERE

INSERT FIGURE 3 HERE

In order to assess how far variability in infant RSA was specifically associated with housing density relative to other associated variables, two separate multiple regression analyses were calculated. The sample size for these ($N=82$) was above the ratio of $50+(8*k)$ recommended as the minimum sample size for multiple regression analyses (Tabachnick, Fidell, & Ullman, 2007). Prior to running the regressions, key assumptions (e.g., normality, homoscedasticity, residuals uncorrelated with predictors) were examined via residual analysis and plots in the usual manner (Tabachnick et al., 2007), and were found not to be violated.

The first analysis (Table 3) was calculated to predict RSA based on other socio-economic variables, namely housing density, maternal education and household income. Of note, since the aim was to ascertain whether the influence of housing density was independent of maternal education and household income, the fact that housing density was not correlated with either maternal education ($r=-.08$) or household income ($r=-.03$) (see Table 1) means that problems of multicollinearity do not affect our interpretation of the findings. Multicollinearity only affects the interpretation of multiple regression analyses where the aim is to compare the

relative influence of variables that are themselves correlated⁵). The overall fit of the model was $F=3.31$, $p=.025$, $R^2=.13$. Housing density was returned as a significant predictor of RSA ($p=.003$); the other two variables were not ($p=.864/.975$).

INSERT TABLE 3 HERE

The second analysis (Table 4) was calculated to predict RSA based on other indices of lifelong stress, namely adverse life events and stressful events around birth in addition to housing density. The overall fit of the model was $F=3.63$, $p=.017$, $R^2=.14$. Housing density was returned as a significant predictor of RSA ($p=.002$); the other two variables were not ($p=.637/.845$).

INSERT TABLE 4 HERE

Analysis 2 - association between housing density and cognitive performance in infants in the lab.

Table 5 shows descriptive statistics for our primary behavioural outcome data. The following analyses are all based on infants from the main sample (see Table 1).

INSERT TABLE 5 HERE

⁵ <https://statisticalhorizons.com/multicollinearity>
<https://blog.minitab.com/blog/adventures-in-statistics-2/what-are-the-effects-of-multicollinearity-and-when-can-i-ignore-them>

Test 1 – visual recognition memory. A significant relationship was observed between housing density and visual recognition memory (Fig 2f, 2i) ($q=.37$, $p=.033$) (increased housing density associated with superior recognition memory, defined as an increased proportion looking time to the unfamiliarised face). Subsequent analyses suggested that these relationships were independent of eyetracking data quality, as quantified using either of the two commonly measured parameters (Wass et al., 2014), flicker $Z=.56$, $p=.57$ or precision $Z=1.52$, $p=.23$. These results suggest that increased housing density associated with increased visual recognition memory.

Test 2 – sustained attention. A significant negative correlation was observed between housing density and sustained attention (Fig 2g, 2j) ($q=-.38$, $p=.01$) (increased housing density associated with reduced sustained attention, defined as shorter look durations towards novel objects). We also examined the physiological correlates of sustained attention by examining infants' heart rate decelerations relative to the appearance of an attractive, attention-eliciting stimulus (Fig 2j). Previous research has suggested that greater heart rate decelerations associate with better quality sustained attention, as indicated by other measures such as information retention and distractibility (Richards, 2010). For this time series analysis, a group analysis was conducted using a median split based on housing density (see Methods), and the significance of group differences was estimated using permutation-based temporal clustering analyses (see Methods). Results suggested that no group differences were observed in heart rate decelerations during the initial period following the appearance of an attractive novel stimulus, but that significant ($p<.001$) group differences emerged during the period 30-60 seconds following stimulus onset (see Fig 2j). These results suggest that increased housing density associated with lower sustained attention.

Test 3 - emotion regulation. A significant negative association was observed between housing density and emotion regulation ($q=-.29$, $p=.041$) (increased housing density associated with worse emotion regulation, defined as the change in facial affect during the still face). In addition, significant relationships were observed between housing density and increase in heart rate during the still face period (see Fig 2k) ($q=.61$, $p=.007$) (increased housing density associated with greater increase in heart rate during the still face). A significant relationship was also observed between housing density and decrease in heart rate after the still face period ($q=-.48$, $p=.04$) (increased housing density associated with greater recovery in heart rate following the still face).

Control analysis. Mean (S.E.) HR in BPM during the free play session immediately preceding the still face was 131.7 (2.9)/136.6 (2.4) for the low/high housing density groups respectively. Mean HR during the still face was 139.0 (3.4)/144.4 (2.4) for the low/high housing density groups, and during the recovery period following the still face was 132.9 (3.4)/133.0 (2.0). In order to ensure that these differences in baseline heart rate did not influence the change scores observed during the still face procedure (see e.g. Richards, 1980), we also conducted an additional analysis in which the mean HR scores during still face were regressed on the mean HR scores during the free play, and the residuals were calculated. A greater residual score indicates that a greater increase in HR was observed during the still face, after controlling for differences in baseline HR. A significant positive relationship was observed between housing density and increase in HR during the still face, after controlling for baseline HR ($q=.57$, $p=.01$), replicating the relationship documented above. However, after controlling for HR during the still face, the relationship between housing density and recovery after the still face period became non-significant ($q=-.423$, $p=.36$). Overall, the results from this control analysis

agree with the main analysis in suggesting that increased housing density is associated with poorer emotion regulation.

Test 4 – neural data. Figure 4a shows the absolute power across the entire scalp, subdivided by high/low housing density. Figure 4b shows topoplots of relative theta power during segments while infants were visually attending to the stimuli. Figure 4c shows the relative theta power during visual attention over a selection of vertex electrodes only, compared between high and low housing density groups. A significant relationship was observed between housing density and relative theta power ($q=.39$, $p=.037$) (increased housing density associated with increased relative theta power).

In addition, we examined the co-fluctuation between theta activity and look duration (Figure 4d, 4e). We used the same methods as a previous study that showed that, in infants, shifts in visual attention are reliably preceded by increases in relative theta power (Wass, Noreika, et al., 2018). Multiple comparisons were corrected for using permutation-based clustering tests (see Methods). This suggested that, for the high ($p=.016$) but not the low ($p=n.s.$) housing density group, a significant association between theta power and look duration was observed during the time windows -1 to 0 seconds (brain activity predicting subsequent looking behaviour) and 0 to 1 seconds (looking behaviour predicting subsequent brain activity). These relationships closely replicate previous observed results, from a different sample (Wass et al., in press). Overall, our results suggest that increased housing density was associated with increased theta power during visual attention, and stronger phasic associations between visual attention and theta power.

INSERT FIGURE 4 HERE

Analysis 3 – association between housing density and at-home environmental factors.

We also wished to explore how the following environmental factors differed between HD and LD infants: noise exposure, proportion of time spent at home vs not at home, and movement levels while outdoors (as a proxy for whether infants were allowed to roam freely while outdoors, or strapped into a pushchair or buggy).

INSERT FIGURE 5 HERE

First, we examined infants' ambient levels of noise exposure, comparing segments when infants were at home and not at home, and when waking and sleeping (see Fig 5a). For these analyses, all segments in which the infant was vocalising were identified via hand-coding (see Wass, Smith, Daubney, et al., 2019 for more information) and excluded from this analysis. Overall, the quietest sections of the data were when infants were at home and asleep. The loudest overall sections were when infants were not home and awake. Sections where infants were not home and asleep were approximately as loud as the sections where infants were home and awake. Paired-sample comparisons showed that ambient microphone noise was higher during the home compared to the not home segments, for both the awake $Z=7.05$ $p<.001$ and the asleep $Z=2.34$ $p=.02$ segments.

Group analyses conducted using a median split based on housing density showed that HD infants spent more time not at home during the day $Z=1.85$ $p=.04$ (Fig 5b). Correspondingly, whereas LD infants spent the majority of their daytime sleeping time at home, infants from the

HD group spent approximately half of their daytime sleeping time outside of the home (Fig 5c).

In addition, we also examined movement levels (using the actigraph), examining just the segments while infants were awake. Movement levels while at home (of which, for the majority of time, infants were free-roaming (allowed to move freely)) were non-significantly higher in the HD group; while not home, however, movement levels were marginally lower in the HD group $Z=1.78$, $p=.07$. One possible explanation for this difference is that the HD group spent less of their time while not at home free roaming, and more time strapped into push-chairs, even when considering just the segments while the infants were awake.

Overall, these results suggest that ambient microphone noise levels were quieter when at home, compared to when not home; HD infants spent more time not home, including a greater proportion of their sleeping time, and thus were exposed to higher levels of sleeping noise. Movement levels while not home were lower in the HD group, which may be because HD infants spent more of their time while outdoors strapped in to push-chairs and buggies.

Discussion

Our results suggest that 12-month-old infants raised in high density environments (henceforth HD infants) show decreased Respiratory Sinus Arrhythmia (RSA), indicating decreased parasympathetic nervous system activity, while at home (Analysis 1). These relationships were independent of socioeconomic status, lifelong stressors and maternal RSA. Although the possibilities of direct genetic linkage, or mediation via other socioeconomic or stress-related factors cannot be ruled out, our finding that infant and mother RSA levels were not significantly associated, and that the relationship between urban living and RSA was independent of these other factors, counts against this possibility. Our findings were also not attributable to differences in the number of other children living in the household, as this showed no relationship to infant RSA.

In the lab (Analysis 2), we found that HD infants show lower sustained attention, along with increased emotion reactivity. However, they showed superior recognition memory for briefly presented stimuli, along with stronger associations between fluctuations in visual attention and fluctuations in theta power (an index of neural engagement). Again, the cross-sectional nature of the study means that strong causal conclusions cannot be drawn. Overall, however, our results are consistent with previous research into the effects of urbanization in adults. This research has suggested that the effect of urbanization may be mediated by the neuromodulatory locus coeruleus – norepinephrine system (Linnell & Caparos, 2020; Linnell, Caparos, & Davidoff, 2014; Aston-Jones & Cohen, 2005), based on a disjunction between ‘top-down’ attention, which is impaired at high levels of stress, and ‘bottom-up’ or stimulus-driven attention, which is increased at high stress (Arnsten, 2009; Luethi et al., 2009). This possibility can, it has been suggested, explain a variety of findings into how urbanization affects adult

cognition, affecting both covert and overt attention (Linnell & Caparos, 2020). Our findings are consistent with these adult findings.

They are also consistent with previous research into how elevated physiological stress affects cognition during infancy and early childhood (Wass, 2018). For example, previous research suggests that increased physiological stress associates with both poorer sustained attention and superior recognition memory in a cohort of small-town-dwelling 12-month-old infants (de Barbaro et al., 2016b; see also Arnsten, 2009). Our results suggesting greater behavioural and physiological reactivity in infants from higher density urban settings are also consistent with previous findings from older children (Evans et al., 2001) (see also Lederbogen et al., 2011). In particular, our finding that associations between visual attention and theta power were stronger in the HD group may provide a way to reconcile previous findings into theta power as an index of engagement and learning (Begus & Bonawitz, 2020) with research suggesting that theta power is elevated in children with more challenging early-life backgrounds (Maguire & Schneider, 2019; Marshall & Fox, 2007).

Our finding that the effects of city life are detectable so early in development rules out several of the mechanisms, such as learnt helplessness, that have previously been suggested as mediating the relationship between urban dwelling, physiological stress and cognitive performance (Wells, 2000). Regrettably, however, a full discussion of possible mechanisms that may mediate the relationships we observed between HD environments, physiological stress and cognitive performance is beyond the scope of this paper. Nevertheless, our home data recordings offer some insight into how the environment differs between the HD and LD infants (Fig 5), which may suggest directions for future work. For all infants, ambient microphone noise levels were markedly quieter when at home, compared to when not home

(Fig 5a); HD infants spent more time not home (Fig 5b), including a greater proportion of their sleeping time (Fig 5c), and thus were exposed to much higher levels of sleeping noise. Although it is possible that these differences may relate to the degree to which people outside the household are involved in primary care giving, this was not so in the present study, as parents were asked to participate on days when they would be spending the entire day with their child. They are likely, however, to reflect differences in living styles, with HD families likely to spend more time not at home. In addition to direct effects of noisier outdoor environments on stress (Wass, Smith, Daubney, et al., 2019) there are also other effects of being outdoors, such as traffic-related air pollution (Sunyer et al., 2015), and exposure to strangers. Future work should investigate these factors in more detail.

We have also highlighted that, while movement levels at home were comparable between the HD and LD groups, movement levels while not home were lower in the HD group. Although we did not directly measure this in this study, this may be because HD infants spent more of their time while outdoors strapped in to push-chairs and buggies (Fig 5d). This may be important because recent research suggests that children spontaneously adjust their movement levels to compensate for differing levels of external environmental stimulation (Wass, 2020) – which would be impossible while strapped into a pushchair. The fact that, even by 12 months, LD infants spend more of their time free-roaming may also be important because of the known associations between aerobic exercise and stress (Ludyga et al., 2018) – although these remain under-researched in infants and young children.

Future work should investigate these possible mediating variables in more detail. They should also investigate other possible mediating variables that we were not able to track in this study, but which are also likely to mediate the relationship between HD environments and

physiological stress, such as media use (Beyens, Valkenburg, & Piotrowski, 2018) and differences in caregiver/parenting styles (Glynn & Baram, 2019). Importantly, future work should also repeat the measures we have taken here, but longitudinally, to gain more insight into longitudinal developmental trajectories. Finally, future work should also examine how far these findings generalise to other measures of physiological stress, in addition to RSA.

In future, it will also be interesting to examine whether some children are more sensitive to environmental influences than others (Dich, Doan, & Evans, 2017; Lercher, Evans, & Widmann, 2013). Given research suggesting that repeated evocation of a stress response can lead both to increased levels of long-term physiological stress and hypersensitisation of the stress response (Ulrich-Lai & Herman, 2009), it may be that spending early life in HD environments leads to increased sensitivity to subsequent environmental influences when they occur. Recent research has suggested that increased sensitivity, arising from early life stress, may operate over longer time-frames as both a risk, or an opportunity, factor contingent on context (Hartman, Freeman, Bales, & Belsky, 2018). Longitudinal studies examining the long-term consequences of early exposure to HD environments can examine this hypothesis in more detail.

Future work should also examine how the profile of cognitive strengths, and weaknesses, that we have documented here could be exploited in order to optimise early learning potentials for children from high density urban environments. Understanding the relative strengths of different modes of learning may be more effective than simply attempting to remediate the deficits observed in faculties such as sustained attention.

Supplementary references

Jones et al., 2015

Delorme, Sejnowski, & Makeig, 2007

Jung et al., 2000

Delorme & Makeig, 2004

Berntson, Cacioppo, Quigley, & Fabro, 1994; Berntson et al., 1997

Billman, 2013

Vest et al., 2018

References

- Anrep, G. V., Pascual, W., & Rossler, R. (1935). Respiratory variations of the heart rate. I. The reflex mechanism of the respiratory arrhythmia. . *Royal Society of London Proceedings.Series B*, 119, 191-217.
- Arnsten, A. F. (2009). Stress signalling pathways that impair prefrontal cortex structure and function. *Nature reviews. Neuroscience*, 10(6), 410-422. doi:10.1038/nrn2648
- Arnsten, A. F., & Goldman-Rakic, P. S. (1998). Noise stress impairs prefrontal cortical cognitive function in monkeys: evidence for a hyperdopaminergic mechanism. *Archives of General Psychiatry*, 55(4), 362-368.
- Aston-Jones, G., & Cohen, J. D. (2005). An integrative theory of locus coeruleus-norepinephrine function: Adaptive gain and optimal performance. *Annual Review of Neuroscience*, 28, 403-450. doi:10.1146/annurev.neuro.28.061604.135709
- Begus, K., & Bonawitz, E. (2020). The rhythm of learning: theta oscillations as an index of active learning in infancy. *Developmental Cognitive Neuroscience*, 100810.
- Begus, K., Gliga, T., & Southgate, V. (2016). Infants' preferences for native speakers are associated with an expectation of information. *Proceedings of the National Academy of Sciences*, 113(44), 12397-12402.
- Begus, K., Southgate, V., & Gliga, T. (2015). Neural mechanisms of infant learning: differences in frontal theta activity during object exploration modulate subsequent object recognition. *Biology letters*, 11(5), 20150041.
- Bell, M. A. (2002). Power changes in infant EEG frequency bands during a spatial working memory task. *Psychophysiology*, 39(4), 450-458. doi:10.1017/s0048577201393174
- Berger, A., Tzur, G., & Posner, M. I. (2006). Infant brains detect arithmetic errors. *Proceedings of the National Academy of Sciences*, 103(33), 12649-12653.

- Berman, M. G., Jonides, J., & Kaplan, S. (2008). The cognitive benefits of interacting with nature. *Psychological science, 19*(12), 1207-1212.
- Berntson, G. G., Cacioppo, J. T., Quigley, K. S., & Fabro, V. T. (1994). Autonomic space and psychophysiological response. *Psychophysiology, 31*(1), 44-61.
doi:10.1111/j.1469-8986.1994.tb01024.x
- Berntson, G. G., Thomas Bigger, J., Eckberg, D. L., Grossman, P., Kaufmann, P. G., Malik, M., . . . Stone, P. H. (1997). Heart rate variability: origins, methods, and interpretive caveats. *Psychophysiology, 34*(6), 623-648.
- Beyens, I., Valkenburg, P. M., & Piotrowski, J. T. (2018). Screen media use and ADHD-related behaviors: Four decades of research. *Proceedings of the National Academy of Sciences, 115*(40), 9875-9881.
- Billman, G. E. (2013). The LF/HF ratio does not accurately measure cardiac sympatho-vagal balance. *Frontiers in physiology, 4*.
- Brandes-Aitken, A., Braren, S., Swingler, M., Voegtline, K., & Blair, C. (2019). Sustained attention in infancy: A foundation for the development of multiple aspects of self-regulation for children in poverty. *Journal of Experimental Child Psychology, 184*, 192-209.
- Bryck, R. L., & Fisher, P. A. (2012). Training the brain: practical applications of neural plasticity from the intersection of cognitive neuroscience, developmental psychology, and prevention science. *American psychologist, 67*(2), 87.
- Buschman, T. J., & Miller, E. K. (2007). Top-down versus bottom-up control of attention in the prefrontal and posterior parietal cortices. *Science, 315*(5820), 1860-1862.
- Colombo, J., & Mitchell, D. W. (2009). Infant visual habituation. *Neurobiology of learning and memory, 92*(2), 225-234. doi:10.1016/j.nlm.2008.06.002

- Courage, M. L., Reynolds, G. D., & Richards, J. E. (2006). Infants' attention to patterned stimuli: Developmental change from 3 to 12 months of age. *Child Development*, 77(3), 680-695.
- Dayan, P., & Yu, A. J. (2003). Uncertainty and learning. *IETE Journal of Research*, 49(2-3 SPEC.), 171-181.
- de Barbaro, K., Clackson, K., & Wass, S. V. (2016a). Infant attention is dynamically modulated with changing arousal levels. *Child Development*, 88(2), 629-639. doi:10.1111/cdev.12689
- de Barbaro, K., Clackson, K., & Wass, S. V. (2016b). Stress reactivity may enhance basic learning processes in infants. . *Developmental psychobiology*, 1, 1-15.
- Delorme, A., & Makeig, S. (2004). EEGLAB: an open source toolbox for analysis of single-trial EEG dynamics including independent component analysis. *Journal of neuroscience methods*, 134(1), 9-21.
- Delorme, A., Sejnowski, T., & Makeig, S. (2007). Enhanced detection of artifacts in EEG data using higher-order statistics and independent component analysis. *NeuroImage*, 34(4), 1443-1449.
- Dich, N., Doan, S. N., & Evans, G. W. (2017). In risky environments, emotional children have more behavioral problems but lower allostatic load. *Health psychology*, 36(5), 468.
- Evans, G. W. (2006). Child development and the physical environment. *Annu. Rev. Psychol.*, 57, 423-451.
- Evans, G. W., Lercher, P., Meis, M., Ising, H., & Kofler, W. W. (2001). Community noise exposure and stress in children. *The Journal of the Acoustical Society of America*, 109(3), 1023-1027.

- Foote, S. L., Freedman, R., & Oliver, A. P. (1975). Effects of putative neurotransmitters on neuronal activity in monkey auditory cortex. *Brain Research*, 86(2), 229-242.
- Glynn, L. M., & Baram, T. Z. (2019). The influence of unpredictable, fragmented parental signals on the developing brain. *Frontiers in neuroendocrinology*.
- Ham, J., & Tronick, E. (2009). Relational psychophysiology: Lessons from mother–infant physiology research on dyadically expanded states of consciousness. *Psychotherapy Research*, 19(6), 619-632.
- Hartley, D. (2004). Rural health disparities, population health, and rural culture. *American Journal of Public Health*, 94(10), 1675-1678.
- Hartman, S., Freeman, S. M., Bales, K. L., & Belsky, J. (2018). Prenatal Stress as a Risk—and an Opportunity—Factor. *Psychological science*, 29(4), 572-580.
- Joëls, M., & Baram, T. Z. (2009). The neuro-symphony of stress. *Nature Reviews Neuroscience*, 10(6), 459.
- Jones, E. J. H., Goodwin, A., Orekhova, E., Charman, T., Dawson, G., Webb, S., & Johnson, M. (2020). Infant EEG theta modulation predicts childhood intelligence. *Scientific reports*, 10(1), 1-10.
- Jones, E. J. H., Venema, K., Lowy, R., Earl, R. K., & Webb, S. J. (2015). Developmental changes in infant brain activity during naturalistic social experiences. *Developmental psychobiology*, 57(7), 842-853.
- Jung, T.-P., Makeig, S., Humphries, C., Lee, T.-W., Mckeown, M. J., Iragui, V., & Sejnowski, T. J. (2000). Removing electroencephalographic artifacts by blind source separation. *Psychophysiology*, 37(2), 163-178.
- Lederbogen, F., Kirsch, P., Haddad, L., Streit, F., Tost, H., Schuch, P., . . . Deuschle, M. (2011). City living and urban upbringing affect neural social stress processing in humans. *Nature*, 474(7352), 498.

- Lercher, P., Evans, G. W., & Widmann, U. (2013). The ecological context of soundscapes for children's blood pressure. *The Journal of the Acoustical Society of America*, 134(1), 773-781.
- Linnell, K. J., & Caparos, S. (2020). Urbanisation, the Arousal System, and Covert and Overt Attentional Selection. *Current Opinion in Psychology*, 32(2020), 100-104.
- Linnell, K. J., Caparos, S., & Davidoff, J. (2014). Urbanization increases left-bias in line-bisection: an expression of elevated levels of intrinsic alertness? *Frontiers in Psychology*, 5, 1127.
- Linnell, K. J., Caparos, S., de Fockert, J. W., & Davidoff, J. (2013). Urbanization decreases attentional engagement. *Journal of Experimental Psychology: Human Perception and Performance*, 39(5), 1232.
- Liston, C., McEwen, B. S., & Casey, B. J. (2009). Psychosocial stress reversibly disrupts prefrontal processing and attentional control. *Proceedings of the National Academy of Sciences of the United States of America*, 106(3), 912-917.
- Ludyga, S., Gerber, M., Mücke, M., Brand, S., Weber, P., Brotzmann, M., & Pühse, U. (2018). The acute effects of aerobic exercise on cognitive flexibility and task-related heart rate variability in children with ADHD and healthy controls. *Journal of Attention Disorders*, 1087054718757647.
- Luethi, M., Meier, B., & Sandi, C. (2009). Stress effects on working memory, explicit memory, and implicit memory for neutral and emotional stimuli in healthy men. *Frontiers in behavioral neuroscience*, 2, 5.
- Maguire, M. J., & Schneider, J. M. (2019). Socioeconomic status related differences in resting state EEG activity correspond to differences in vocabulary and working memory in grade school. *Brain and cognition*, 137, 103619.

- Maris, E. (2012). Statistical testing in electrophysiological studies. *Psychophysiology*, 49(4), 549-565.
- Maris, E., & Oostenveld, R. (2007). Nonparametric statistical testing of EEG-and MEG-data. *Journal of neuroscience methods*, 164(1), 177-190.
- Marshall, P. J., & Fox, N. A. (2007). A comparison of the electroencephalogram (EEG) between institutionalized and community children in Romania (vol 16, pg 1327, 2004). *Journal of Cognitive Neuroscience*, 19(1), 173-174.
- Minor, T. R., Jackson, R. L., & Maier, S. F. (1984). Effects of task-irrelevant cues and reinforcement delay on choice-escape learning following inescapable shock: evidence for a deficit in selective attention. *Journal of Experimental Psychology: Animal Behavior Processes*, 10(4), 543.
- Oakes, L. M., Baumgartner, H. A., Barrett, F. S., Messenger, I. M., & Luck, S. J. (2013). Developmental changes in visual short-term memory in infancy: evidence from eye-tracking. *Frontiers in Psychology*, 4. doi:10.3389/fpsyg.2013.00697
- Obasanjo, O. O. (1999). *The impact of the physical environment on adolescents in the inner city*. ProQuest Information & Learning.
- Orehova, E. V., Stroganova, T. A., & Posikera, I. N. (1999). Theta synchronization during sustained anticipatory attention in infants over the second half of the first year of life. *International Journal of Psychophysiology*, 32(2), 151-172. doi:10.1016/s0167-8760(99)00011-2
- Orehova, E. V., Stroganova, T. A., & Posikera, I. N. (2001). Alpha activity as an index of cortical inhibition during sustained internally controlled attention in infants. *Clinical Neurophysiology*, 112(5), 740-749. doi:10.1016/s1388-2457(01)00502-8
- Porges, S. W. (2007). The polyvagal perspective. *Biological Psychology*, 74(2), 116-143. doi:10.1016/j.biopsycho.2006.06.009

- Razza, R. A., Martin, A., & Brooks-Gunn, J. (2010). Associations Among Family Environment, Sustained Attention, and School Readiness for Low-Income Children. *Developmental Psychology*, 46(6), 1528-1542. doi:10.1037/a0020389
- Richards, J. E. (1980). The statistical analysis of heart rate - a review emphasizing infancy data. *Psychophysiology*, 17(2), 153-166.
- Richards, J. E. (2010). The development of attention to simple and complex visual stimuli in infants: Behavioral and psychophysiological measures. *Developmental Review*, 30(2), 203-219. doi:10.1016/j.dr.2010.03.005
- Richards, J. E. (2011). Infant Attention, Arousal and the Brain. In L. M. Oakes, C. H. Chason, M. Casasola, & D. H. Rakison (Eds.), *Infant Perception and Cognition* Oxford, UK: Oxford University Press.
- Richman, N. (1977). Behaviour problems in pre-school children: Family and social factors. *The British Journal of Psychiatry*, 131(5), 523-527.
- Rose, S. A., Feldman, J. F., & Jankowski, J. J. (2012). Implications of infant cognition for executive functions at age 11. *Psychological science*, 23(11), 1345-1355. doi:10.1177/0956797612444902
- Rose, S. A., Wass, S., Jankowski, J. J., Feldman, J. F., & Djukic, A. (2017). Sustained attention in the face of distractors: A study of children with Rett syndrome. *Neuropsychology*, 31(4), 403.
- Ruff, H. A., & Capozzoli, M. C. (2003). Development of attention and distractibility in the first 4 years of life. *Developmental Psychology*, 39(5), 877-890. doi:10.1037/0012-1649.39.5.877
- Ruff, H. A., & Rothbart, M. K. (1996). *Attention in early development: Themes and variations*: New York: Oxford University Press.

Stroganova, T. A., Orekhova, E. V., & Posikera, I. N. (1999). EEG alpha rhythm in infants.

Clinical Neurophysiology, 110(6), 997-1012. doi:10.1016/s1388-2457(98)00009-1

Sunyer, J., Esnaola, M., Alvarez-Pedrerol, M., Forns, J., Rivas, I., López-Vicente, M., . . .

Basagaña, X. (2015). Association between traffic-related air pollution in schools and cognitive development in primary school children: a prospective cohort study. *Plos Medicine*, 12(3), e1001792.

Tabachnick, B. G., Fidell, L. S., & Ullman, J. B. (2007). *Using multivariate statistics* (Vol. 5): Pearson Boston, MA.

Ulrich-Lai, Y. M., & Herman, J. P. (2009). Neural regulation of endocrine and autonomic stress responses. *Nature Reviews Neuroscience*, 10(6), 397-409. doi:10.1038/nrn2647

UNICEF. (2019). *Advantage or Paradox? The Challenge for Children and Young People of Growing Up Urban*. . Retrieved from

Vest, A. N., Da Poian, G., Li, Q., Liu, C., Nemati, S., Shah, A. J., & Clifford, G. D. (2018). An open source benchmarked toolbox for cardiovascular waveform and interval analysis. *Physiological measurement*, 39(10), 105004.

Wass, S. V. (2014). Comparing methods for measuring peak look duration: are individual differences observed on screen-based tasks also found in more ecologically valid contexts? . *Infant Behavior and Development*., 37(3), 315-325.

Wass, S. V. (2018). How orchids concentrate? The relationship between physiological stress reactivity and cognitive performance during infancy and early childhood. *Neuroscience & Biobehavioral Reviews*.

Wass, S. V. (2020). Fall asleep or freeze? In home settings, extreme low and high levels of ambient noise associate with reductions in infants' spontaneous movement.

Wass, S. V., Clackson, K., Georgieva, S. D., Brightman, L., Nutbrown, R., & Leong, V.

(2018). Infants' visual sustained attention is higher during joint play than solo play: is

this due to increased endogenous attention control or exogenous stimulus capture?

Developmental Science.

Wass, S. V., de Barbaro, K., & Clackson, K. (2015). Tonic and phasic co-variation of peripheral arousal indices in infants. *Biological Psychology*, 111, 26-39.

Wass, S. V., Forssman, L., & Leppanen, J. (2014). Robustness and Precision: How Data Quality May Influence Key Dependent Variables in Infant Eye-Tracker Analyses. *Infancy*, 19(5), 427-460.

Wass, S. V., Noreika, V., Georgieva, S., Clackson, K., Brightman, L., Nutbrown, R., . . . Leong, V. (2018). Parental neural responsivity to infants' visual attention: how mature brains influence immature brains during social interaction. *PLoS Biology*, 16(12), e2006328.

Wass, S. V., Noreika, V., Georgieva, S. D., Clackson, K., Brightman, L., Nutbrown, R., . . . Leong, V. (in press). Parental neural responsivity to infants' visual attention: how mature brains influence immature brains during social interaction. *PLoS Biology*.

Wass, S. V., Phillips, E., Marriott Haresign, I., Whitehorn, M., Clackson, K., Georgieva, S., . . . Leong, V. (pre-print). Parental frontal brain activity tracks infants' attention during shared play.

Wass, S. V., Smith, C., Clackson, K., & Mirza, F. U. (2020). In infancy, it's the extremes of arousal that are 'sticky': naturalistic data challenge purely homeostatic approaches to studying self-regulation. . *pre-print*. doi:<https://psyarxiv.com/vc98f/>

Wass, S. V., Smith, C. G., Clackson, K., Gibb, C., Eitzenberger, J., & Mirza, F. U. (2019). Parents mimic and influence their infant's autonomic state through dynamic affective state matching. *Current biology*, 29(14), 2415-2422. e2414.

Wass, S. V., Smith, C. G., Daubney, K. R., Suata, Z. M., Clackson, K., Begum, A., & Mirza, F. U. (2019). Influences of environmental stressors on autonomic function in 12-

month-old infants: understanding early common pathways to atypical emotion regulation and cognitive performance. *Journal of Child Psychology & Psychiatry & Allied Disciplines*.

Weinberg, M. K., & Tronick, E. Z. (1996). Infant affective reactions to the resumption of maternal interaction after the still-face. *Child Development*, 67(3), 905-914.

Wells, N. M. (2000). At home with nature: Effects of “greenness” on children’s cognitive functioning. *Environment and behavior*, 32(6), 775-795.

Xie, W., Mallin, B. M., & Richards, J. E. (2018). Development of infant sustained attention and its relation to EEG oscillations: an EEG and cortical source analysis study. *Developmental Science*, 21(3), e12562.

Tables

Table 1: Demographic details for the main (N=57) sample. Equivalent data for the expanded (N=82) sample are given in the SM (section 1.2, Table S1).

Infant age (days) – mean		351.7
- SE		7.7
Gender (% male)		43.9
Infant Ethnicity (%)	White British	39.6
	Other white	15.1
	Afro-Caribbean	13.2
	Asian, Indian & Pakistani	11.3
	Mixed - White/Afro-Carib	5.7
	Mixed - White/Asian	9.4
	Other mixed	5.7
Household Income (%)	Under £16k	35.3
	£16-£25k	17.6
	£26-£35k	15.7
	£36-£50k	9.8
	£51-£80k	13.7
	>£80k	7.8
Maternal education (%)	Postgraduate	21.6
	Undergraduate	56.9
	FE qualification	3.9
	A-level	2.0
	GCSE	9.8
	No formal qualifications	3.9
	Other	3.9

*Table 2 Bivariate correlations between continuous variables. * indicates the significance of the bivariate correlations. * - $p < .05$; ** - $p < .01$*

	1	2	3	4	5	6	7	8
1 – Infant RSA	-							
2 - Housing density	-.37**	-						
3 – Mother occupation	-.02	.10	-					
4 - Father occupation	.04	.24*	.28*	-				
5 - Mother education	-.08	.24*	.37**	.29**	-			
6 - Household income	-.03	.22*	.59**	.60**	.40**	-		
7 - Adverse life events	-.09	.07	.21*	.13	.20	.30**	-	
8 - Stressful events around birth	-.09	.13	.07	.21*	.23*	.24*	.27**	-
9 – Mother RSA	-.01	.08	-.13	-.08	.11	-.09	0.11	-.18

Table 3: Results of multiple regression to predict RSA based on housing density, maternal education, household income.

	B	SE	β	p
Housing density	-.013	.004	-.36	.003
Maternal education	.054	.314	.02	.864
Household income	-.008	.263	-.004	.975

Table 4: Results of multiple regression to predict RSA based on housing density, adverse life events and stressful events around birth.

	B	SE	β	p
Housing density	-.013	.004	-.36	.002
Adverse life events	-.093	.197	-.056	.637
Stressful events around birth	.052	.264	.024	.845

Table 5: Descriptive statistics table showing the mean (st.err.) values for our main dependent variables, for the whole group and split using a median split into high/low density housing groups.

	Whole group	High Density (med. split)	Low Density (med split)
Visual recognition memory (proportion looking to novel target)	.567 (.019)	.550 (.027)	.584 (.027)
Sustained attention (z-score - composite of three tasks)	-.079 (.090)	.049 (.108)	-.212 (.141)
Emotion regulation (β - change in affect during still face)	-.016 (.005)	-.011 (.007)	-.019 (.008)
Neural engagement (ρ – relative theta power during visual attention)	.020 (.002)	.015 (.003)	.024 (.004)

Figures

Figure 1: Equipment and raw data illustrations from the home visit. Top left: illustration showing the two layers – vest and T-shirt – that the infant wore; picture of infant wearing the equipment. Top right: sample frames from wearable camera worn by the participant. Below: illustrations of the raw data collected from a single participant over the course of a single day. From top to bottom: RR intervals in Beats Per Minute; Heart rate variability (Root Mean Square of Successive Differences); Actigraphy; Microphone Sound (decibels); GPS (km from home); coding of microphone ambient data.

Figure 2: a) sample illustrations showing respiratory sinus arrhythmia in the heart rate data (see e for group comparison). The sample illustrates the change in heart rate during the first 40 minutes of sleep in two infants - one showing low RSA (top) and one high RSA (bottom); b) excerpts showing a 15-second segment of data from the same two samples; c) Poincaré plots of the two samples, illustrating greater inter-beat variability in the lower sample; d) Fourier plots of the two samples, illustrating increased power in the 0.5 Hz range, corresponding to the respiration cycle; e) scatterplot showing mean RSA during all data recorded while the infants were at home and awake, subdivided into HD/LD groups using a median split (see Methods). Red bars show the per-group means; f) schematic illustrating the visual recognition memory task; g) schematic illustrating the sustained attention task; h) schematic showing the still face task; i) illustration of how eyetracker data were coded for visual recognition memory task; j) sustained attention - change in heart rate over time relative to the appearance of an attractive,

attention-eliciting stimulus, subdivided by HD/LD group; k) change in heart rate over time during free play/still face task, subdivided by HD/LD group. For j, star shows the area identified as showing significant group differences in the cluster-based permutation analysis. For j and k, shaded areas show the S.E.

Figure 3: Infant RSA values subdivided by a) household income; b) maternal education; c) housing density. Units for RSA are RMSSD. * indicates significant relationship between the x-axis variable and RSA, * - $p < .01$

Figure 4: a) Fourier plots showing frequency against absolute power over vertex electrodes. Infants from the high housing density group are shown in blue, those from the low density group in red. b) topoplots showing the distribution of absolute theta (3-6Hz) power for the high housing density group and the low housing density group. c) Bar chart showing the difference in mean relative theta, split by housing density group, across vertex electrodes only. d) illustration showing the raw data inputted into the analysis shown in Fig e. Top: sample screenshots from the movie. Looking behaviour during the presentation of a series of attractive videos was coded, and epoched into 4Hz bins. Theta power was also epoched into

4Hz bins using a moving window analysis. The cross-correlation between attention and theta power was calculated. e) topoplots showing the cross-correlation between looking activity and theta, split by high/low housing density. Top: HD group; bottom: LD group. Each column shows the cross-correlation during a different time window, from -5 (brain activity to looking behaviour 5 seconds after that moment) to +5 (looking behaviour to brain activity 5 seconds after that moment). The red box highlights the two windows showing significant associations between looking activity and theta power following the permutation-based clustering analysis.

Figure 5: a) average ambient microphone volumes for all infants while home/not home and awake/asleep; b) Average hours per day spent not at home; blue – high housing density group; red – low housing density group. * - shows significance of statistical analyses described in the main text $* < .05$. c) Proportion of daytime samples sleeping while the infant was home (left) and not home (right); d) average waking movement levels while awake – home (left) vs not home (right)).

Supplementary materials for:

Physiological stress, sustained attention and cognitive engagement in 12-month-old infants growing up in urban environments.

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1 Supplementary methods

1.1 Participants

Figure S1 shows the approximate living locations of the participants, with population density statistics.

Figure S1: Approximate living locations for all participants in the study. In the top-left picture, the Southern area highlighted in red shows the living locations of the N=57 group who comprised the Main sample for the study. The Northern area shows the living locations of the additional cohort who added to the Expanded sample for the study. Colour gradient shows urban density, measured in people/per hectare. Bottom right: histogram showing the distribution of participants' housing type, subdivided between: detached or semi-detached house/terraced house/small apartment block (<5 stories); large apartment block (>5 stories).

1.2 Demographic data for the expanded (N=82) sample*Table S1: Demographic details for the expanded sample (N=82)*

Infant age (days) – mean		351.9
- SE		4.6
Gender (% male)		39.3
Infant Ethnicity (%)	White British	51.9
	Other white	11.4
	Afro-Caribbean	8.9
	Asian, Indian & Pakistani	10.1
	Mixed - White/Afro-Carib	2.5
	Mixed - White/Asian	7.6
	Other mixed	7.6
Household Income (%)	Under £16k	30.4
	£16-£25k	29.1
	£26-£35k	11.4
	£36-£50k	12.7
	£51-£80k	8.9
	>£80k	7.6
Maternal education (%)	Postgraduate	34.2
	Undergraduate	49.4
	FE qualification	2.5
	A-level	3.8
	GCSE	5.1
	No formal qualifications	2.5
	Other	1.3

1.3 Artifact rejection procedure for EEG data

The artifact rejection procedure was based on previous research (Wass et al., 2018). The procedure involved seven separate stages.

At Stage 1, a band-pass filter was applied to exclude activity below 1Hz and above 16Hz. At Stage 2, noisy channels were identified using two criteria. The first criterion involved calculating the power spectrum with Fast Fourier Transform (FFT) and summing the total power across the frequency spectrum. Channels for which the total power was greater than two inter-quartile ranges above the mean total power for all channels were excluded. The mean (st.err.) number of channels identified using this criterion was 11.2 (0.83). The second criterion involved identifying, and excluding, channels for which the total power was greater than 1 IQR away from the average of the six nearest neighbouring channels (see Jones, Venema, Lowy, Earl, & Webb, 2015 for a similar approach). The mean (st.err.) number of channels identified using this criterion was 8.7 (0.52). In addition, the total power across the entire frequency spectrum was visually inspected for each channel at this stage, and data from 9 infants were excluded because the total power for all channels was markedly above the average total across all infants, and because visual inspection of the data confirmed that this was not due to factors such as sporadic noisy segments, or to ground noise that could be removed via ICA. Only infants with average power values of $>500 \mu\text{V}$ were excluded; mean (st.err.) power for the remaining participants was 27.2 (4.5).

At Stage 3, Continuous data were then segmented into two-second epochs, and the most egregious sections of noisy data were excluded prior to running the ICA. This was done by calculating the max-min change on a per-channel, per-epoch basis, across all channels and epochs, and excluding channels in which the difference was above a threshold of $\pm 3000 \mu\text{V}$. 10.4% of epochs were excluded at this initial rejection stage.

At Stage 4, an extended ICA algorithm was run using the runica algorithm implemented within EEGLAB in Matlab (Delorme, Sejnowski, & Makeig, 2007). The time-courses and spatial distributions of the ICs were visually inspected and the components accounting for ground noise, eye blinks, eye movements and other muscular and movement artifacts were then manually marked and removed (Jung et al., 2000). At Stage 5, channels that had been excluded at stage 3 were interpolated using the spherical interpolation function from EEGLAB (Delorme & Makeig, 2004). At Stage 6, a second max-min criterion was applied, identical to that applied at stage three but with more stringent criteria. For each epoch and for each channel, the max-min value was calculated. Epochs showing a difference $>\pm 80 \mu\text{V}$ were excluded from the adult data. The percentage of epochs excluded at this stage was 16.4%. At Stage 7, data were re-referenced using the average reference.

2 Supplementary Results

2.1 RSA analyses in the frequency domain

In addition to the analyses presented in the text, which are based on RMSSD, we also repeated the same analyses using frequency domain estimates of RSA. These were calculated using the same algorithms as used in the main analyses (Vest et al., 2018). Low Frequency activity (LF-HRV) was defined as $0.04\text{Hz} \leq \text{LF} < 0.15\text{Hz}$, and High Frequency activity (HF-HRV) was defined as $0.15\text{Hz} \leq \text{HF} < 0.4\text{Hz}$. Of note, however, and importantly, these thresholds were optimised for adults, and not for the faster breathing rates of infants, and so many not be optimal for detecting the faster breathing rates of infants.

Traditionally, HF activity is believed to reflect cardiac parasympathetic nerve activity, while LF activity, although more complex, is often assumed to have a dominant sympathetic component (Berntson, Cacioppo, Quigley, & Fabro, 1994; Berntson et al., 1997). However, this conclusion has been challenged by research that both parasympathetic and sympathetic subsystems contribute to both components of the frequency band responses (Billman, 2013). Further, this distinction has been generated based on adult research and may generalise poorly to infants.

Overall, LF-HRV and HF-HRV were strongly correlated with one another ($\rho = .89$, $p < .01$). The RMSSD measure correlates both with LF-HRV ($\rho = .63$, $p < .01$) and with HF-HRV ($\rho = .78$, $p < .01$). Surprisingly, given the strength of these correlations, associations of housing density were, while consistent, slightly weaker and below the significance threshold for both LF-HRV ($\rho = -.20$, $p = .08$) and HF-HRV ($\rho = -.15$, $p = .20$). One possible explanation for this is that the frequency ranges used by the algorithm were not optimally positioned to detect infant respiration-related changes, who typically have faster respiration cycles. This may relate to the high correlation between LF and HF activity. Future work in which the respiration cycles are also directly recorded will allow us to estimate RSA in the frequency domain more precisely.

2.2 Housing density by ethnicity

Figure S2 shows a bar chart illustrating how housing density varied by ethnicity in our sample. An ANOVA indicated that the relationship between ethnicity and housing density was significant in our sample $F(81) = 2.3$, $p = .049$. However, when we examined the relationship between housing density and RSA just in the largest ethnic group in our sample (White), the same significant relationship was observed ($\rho = -.29$, $p = .043$).

Figure S2: Bar chart showing a break-down of housing density by participant ethnicity.

Supplementary References

- Berntson, G. G., Cacioppo, J. T., Quigley, K. S., & Fabro, V. T. (1994). Autonomic space and psychophysiological response. *Psychophysiology*, 31(1), 44-61. doi:10.1111/j.1469-8986.1994.tb01024.x
- Berntson, G. G., Thomas Bigger, J., Eckberg, D. L., Grossman, P., Kaufmann, P. G., Malik, M., . . . Stone, P. H. (1997). Heart rate variability: origins, methods, and interpretive caveats. *Psychophysiology*, 34(6), 623-648.
- Billman, G. E. (2013). The LF/HF ratio does not accurately measure cardiac sympatho-vagal balance. *Frontiers in physiology*, 4.
- Delorme, A., & Makeig, S. (2004). EEGLAB: an open source toolbox for analysis of single-trial EEG dynamics including independent component analysis. *Journal of neuroscience methods*, 134(1), 9-21.
- Delorme, A., Sejnowski, T., & Makeig, S. (2007). Enhanced detection of artifacts in EEG data using higher-order statistics and independent component analysis. *NeuroImage*, 34(4), 1443-1449.
- Jones, E. J., Venema, K., Lowy, R., Earl, R. K., & Webb, S. J. (2015). Developmental changes in infant brain activity during naturalistic social experiences. *Developmental psychobiology*, 57(7), 842-853.
- Jung, T.-P., Makeig, S., Humphries, C., Lee, T.-W., Mckeown, M. J., Iragui, V., & Sejnowski, T. J. (2000). Removing electroencephalographic artifacts by blind source separation. *Psychophysiology*, 37(2), 163-178.
- Vest, A. N., Da Poian, G., Li, Q., Liu, C., Nemati, S., Shah, A. J., & Clifford, G. D. (2018). An open source benchmarked toolbox for cardiovascular waveform and interval analysis. *Physiological measurement*, 39(10), 105004.
- Wass, S. V., Noreika, V., Georgieva, S., Clackson, K., Brightman, L., Nutbrown, R., . . . Leong, V. (2018). Parental neural responsivity to infants' visual attention: how mature brains influence immature brains during social interaction. *PLoS Biology*, 16(12), e2006328.