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The effects of Covid-19 related policies on neurocognitive face processing in the first four years of life

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ABSTRACT

In response to Covid-19, western governments introduced policies that likely resulted in a reduced variety of facial input. This study investigated how this affected neural representations of face processing: speed of face processing; face categorization (differentiating faces from houses); and emotional face processing (differentiating happy, fearful, and neutral expressions), in infants (five or ten months old) and children (three years old). We compared participants tested before (total N = 462) versus during (total N = 473) the pandemic-related policies, and used electroencephalography to record brain activity. Event Related Potentials showed faster face processing in three-year-olds but not in infants during the policies. However, there were no meaningful differences between the two Covid-groups regarding face categorization, indicating that this fundamental process is resilient despite the reduced variety of input. In contrast, the processing of facial emotions was affected: across ages, while pre-pandemic children showed differential activity, during-pandemic children did not neurocognitively differentiate between happy and fearful expressions. This effect was primarily attributed to a reduced amplitude in response to happy faces. Given that these findings were present only in the later neural components (P400 and Nc), this suggests that post-pandemic children have a reduced familiarity or attention towards happy facial expressions.

1. Introduction

Processing faces is an important building block of social competence (Bayet and Nelson, 2019; Junge et al., 2020). Children exhibit an innate preference for faces over non-face-like objects from birth (Johnson et al., 2015). However, extracting specific information such as emotional content from a face is thought to develop rapidly during the first year of life and to refine during childhood (Bayet and Nelson, 2019; Pascalis et al., 2020). This developmental pattern is reported for extraction of stable information in a face, such as its ethnicity (Pascalis et al., 2020), and for dynamic information such as the emotional expression (Bayet and Nelson, 2019; Kuefner et al., 2010). These findings are for instance revealed using electroencephalography (EEG), in which three Event-Related Potentials (ERPs) are often studied in relation to face processing in young children: the N290, P400, and Nc. The N290 and P400 are thought to serve as the pre-cursor of the adult N170, the component reflecting visual processing of faces (Conte et al., 2020; Eimer, 1998). The P400 is also, together with the Nc, thought to reflect familiarity with a stimulus (in infants) or the stimulus' saliency and novelty (in school-aged children; Carver et al., 2003; Conte et al., 2020; Di Lorenzo et al., 2020; Glauser et al., 2022). In typically developing children, the latency of these ERPs decreases with age, representing faster face processing (Di Lorenzo et al., 2020; Kuefner et al., 2010). Differential brain activity, represented by differences in ERP amplitude in response to two stimulus categories, is observed for faces versus non-face-like objects from 3 months onward (youngest age tested) and is rather stable throughout life (for a review see Conte et al., 2020). Between 5 and 7 months of age, ERP amplitudes start to differ in response to emotional expressions (for an overview see e.g. van den Boomen et al., 2019). The specific pattern of neural responses to emotional expression develops until late adolescence (Batty and Taylor, 2006).

Current theories highlight that the quantity and quality of sensory input is essential for neurocognitive development (Pereira et al., 2019; Westermann et al., 2007). These broader developmental theories, such as neuroconstructivism, explain neural development as an ongoing interplay between neural activity, gene expression and the environment (Westermann et al., 2007). Indeed, studies reveal that the development of facial information extraction requires experience with faces (Bayet and Nelson, 2019; Maurer, 2017; Pascalis et al., 2020). This experience is acquired during social interactions. However, children's social

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interactions changed tremendously due to the governmental policies taken in response to the Covid-19 pandemic. For instance, due to day-care closing and social distancing in Western countries, children likely had more interactions with immediate family members, but reduced contact with other individuals. Moreover, children's exposure to adult social interactions in various contexts likely decreased as well. Finally, adults started wearing facemasks covering the nose and mouth, thereby diminishing the input from parts of the face. Overall, pandemic-related alterations in social interactions are expected to lead to a lower variety of facial stimuli input, hypothesized to result in changes in the development of face processing (Carnevali et al., 2021). Putting this hypothesis to the test, this paper investigated what the effect is of reduced variety of input - due to Covid-19 related policies - on neural representations of face processing in the first four years of life. We focus on three facets of face processing: the speed of processing faces in the brain; the relatively fundamental differential brain activity in response to faces versus objects (referred to as face categorization); and the more complex differential brain activity in response to emotional expressions (referred to as emotional face processing).

The effects that Covid-19 related policies have on the development of face processing might be restricted to the speed of face processing in the brain and to emotional face processing, rather than face categorization, given the evidence that infants can categorize faces from birth onwards without the necessity of input (Johnson et al., 2015). The expected lack of effect on face categorization is further substantiated by empirical findings showing that there is stability across infancy and early childhood in ERP signal amplitudes related to face categorization (Di Lorenzo et al., 2020; Kuefner et al., 2010). In contrast, the speed of processing faces (ERP latency) continues to increase (Di Lorenzo et al., 2020; Kuefner et al., 2010) and might thus require input to develop. The necessity of input is further supported by the absence of such latency increase in children that received reduced input due to extreme social neglect (Parker et al., 2005). Furthermore, there is much evidence that underscores the pivotal role of input in the acquisition of the ability to process facial emotions. On the extreme side, infants deprived of visual input due to congenital cataract show reduced behavioural differentiation of expressions later in life (Gao et al., 2013), and those who suffered from extreme social neglect exhibit atypical neurocognitive differentiation of emotional faces (Parker et al., 2005). More nuanced differences in input can also impact emotional face processing, reflected in changes in ERP amplitudes: there is ample evidence that the personality and behaviour of parents – who represent the primary, and arguably most substantial, source of input for infants – can affect the infant's emotional face processing (Bornstein et al., 2011; Bowman et al., 2022; de Haan et al., 2004; Taylor-Colls and Pasco Fearon, 2015). For instance, infants of mothers that are more anxious have higher amplitudes in response to fearful faces (Bowman et al., 2022). Furthermore, characteristics of the child itself also relate to emotional face processing (Safyer et al., 2020; van den Boomen et al., 2021). For instance, five-month-old infants with higher quality of social interaction show differential brain activity between fearful and neutral faces, while those with lower quality of social interaction do not. This phenomenon can be explained by evocative gene-environment correlations in which the child's behaviour evokes responses in others (e.g. a smiling child evokes smiles on its parents' faces; Knafo and Jaffee, 2013; Plomin et al., n.d.). These studies suggest that differences in input early in life are associated with how children process emotional faces, implying that changes in input due to the Covid-19 related policies might affect emotional face processing as well.

Furthermore, there are indications that the development of processing *specific* expressions depends on input of such expressions (Leppänen and Nelson, 2009) and that this specific input might have changed as well during the pandemic. That is, given that the pandemic had adverse effects on adult mental well-being (Cerniglia et al., 2022; Russell et al., 2020; Sperber et al., 2023), the onset of the pandemic could have led to an increased occurrence of fearful or sad expressions by parents to children and a reduction of happy ones. This might affect the development of the emotional face processing brain network, that particularly from 7 months of age onwards is thought to depend on the quality and quantity of input (Leppänen and Nelson, 2009).

Prior studies on the effects of Covid-19 related policies on face processing showed that face masks have immediate effects on school-aged children and adults: they hamper labelling of emotional expressions (Carbon and Serrano, 2021; Prete et al., 2022; Ramdani et al., 2022; Ruba and Pollak, 2020), and could increase the neurocognitive face processing speed (Prete et al., 2022). Note that this suggests that in adults decreased input leads to faster processing, which contradicts the developmental findings of a positive relation between input and processing speed (Di Lorenzo et al., 2020; Kuefner et al., 2010). In addition to these short-term, immediate effects, explicit effects of the Covid-19 related policies have been investigated as well, by contrasting performance of children before versus during the policies. It has been shown that 4- to 6-year-olds tested during the policies label fearful faces less accurately but other emotional expressions equally well (Wermelinger et al., 2022a). Additionally, a small-scale fMRI study involving 9–24-month-olds suggests opposite patterns of activity in the fusiform face area in children tested before versus during the pandemic when they viewed novel and repeated faces (Yates et al., 2023). While various other studies investigated effects of the pandemic on children's social behaviour (Galusca et al., 2023; Shakiba et al., 2023; Tronick and Snidman, 2021; Wermelinger et al., 2022b), to our current knowledge none examined the effects of Covid-19 related policies on face processing speed, face categorization, or emotional face processing in the first years of life. A more comprehensive understanding of how reduced variety of input affects these facets of neurocognitive face processing in the first years of life can provide valuable insights in the mechanisms involved in the development of face processing. Moreover, these findings can offer guidance to caregivers, healthcare providers, and policymakers on possible consequences of Covid-19 related policies on young children.

The current study aimed to investigate the effects of reduced variety of social input resulting from Covid-19 related policies, on speed of face processing, face categorization as well as emotional face processing in infants (5 months; 10 months) and young children (three-year-olds). This study was part of the YOUth study (Onland-Moret et al., 2020) and pre-registered (link: https://www.uu.nl/sites/default/files/Dat%20Request%20form%20YOUth%20200204_vandenBoomen21022022_Website.pdf). We compared children tested before with those during the restrictions (that is, before versus between March 2020 and April 2022). Notably, it was during infancy that the 5- and 10-month-olds in our study were exposed to Covid-19 related policies, while the three-year-olds were not exposed to these during their infancy. This distinction allows us to disentangle effects of reduced variety of input during infancy (in the case of infants) or after infancy (in three-year-olds). Using EEG we recorded neural responses to neutral, fearful and happy facial expressions, and to houses. Within this signal, we extracted three ERP components: the N290, P400, and Nc.

To study speed of face processing, we extracted the latency of the face-evoked N290 component for any face (i.e. regardless of emotional content). We focused the latency analyses on the N290 component evoked by faces only, as latency cannot be reliably determined in other components or in components evoked by objects (houses) in infants (Di Lorenzo et al., 2020). We hypothesized that the N290 latency in response to faces would be affected by the Covid-19 related policies, based on latency differences during development (Di Lorenzo et al., 2020; Kuefner et al., 2010), a lack of such development in case of social neglect (Parker et al., 2005), and faster processing of masked than unmasked faces in adults (Prete et al., 2022). However, we intentionally refrained from specifying the direction of this effect due to divergent trends in prior literature (Di Lorenzo et al., 2020; Kuefner et al., 2010; Prete et al., 2022). We expected largest effects at 5-months, then 10-months, and least substantial or potentially absent for 3-year-olds, based on the increased vulnerability of younger infants to developmental perturbations.

To investigate face categorization, we contrasted amplitudes of responses to neutral faces versus houses. Here, we did not expect any significant effects of the Covid-19 related policies on the amplitudes of any of the components,* based on the stable ERP amplitudes in response to faces throughout early childhood (Di Lorenzo et al., 2020; Kuefner et al., 2010).

Finally, to study emotional face processing, we compared amplitudes of responses to neutral, happy and fearful facial expressions. We hypothesized that a reduced neurocognitive differentiation between expressions, reflected in reduced differences between amplitudes of the ERP signal evoked by the expressions, would be visible in children tested during the Covid-19 related policies compared to those tested before. We predominantly expected effects of the policies on fearful face processing.† Further, we hypothesized these amplitude changes to be larger in 10-month-olds compared to 3-year-olds, thus larger in children that received reduced variety of input during infancy versus those that received typical input during infancy but reduced variety of input later on (note that no data on emotional face processing are available in the dataset at 5 months). This hypothesis is based on the significant development and thus increased vulnerability of processing emotional faces during infancy compared to early childhood.

2. Materials and methods

The current data are part of the YOUth study, a longitudinal cohort study of which the Baby & Child cohort follows infants from pre-birth until seven years of age (Onland-Moret et al., 2020). An overview of all measurements conducted in the YOUth study is available from https://www.uu.nl/en/research/youth-cohort-study. Part of the method description is published on this website. All procedures were performed in compliance with relevant laws and institutional guidelines. The YOUth study was approved by the Medical Research Ethics Committee of the University Medical Center (Protocol: Utrecht YOUth Baby & Kind; ID METC 14–616; approved 17–03–2015). The privacy rights of human subjects have been observed, and all participants' parents provided written informed consent.

2.1. Participants

The final sample consisted of 349 4- to 6- month-old infants (189 male; referred to as 5-month-olds), 351 9- to 11-month-old infants (209 male; referred to as 10-month-olds), and 235 2- to 4-year-old children (157 male; referred to as 3-year-olds). See supplementary information Table S1 for detailed inclusion and demographic information. A subset of participants was selected from the full YOUth sample to create as close as possible age- and gender-matched groups before and during Covid-19 related policies (see the supplementary information SI1 on the test dates and stringency of policies). From the selected group, participants were excluded from analyses due to experimental errors (N = 8); when children did not contribute sufficient data due to excessive motion, or other artifacts (N = 397; see below for details on the analyses); were born pre-mature (N = 37; i.e. at 37 weeks or below); had developmental delays related to social competence according to their caretakers (i.e. (suspected of) having a Communication Disorder or Autism Spectrum Disorder; N = 11). Furthermore, all caretakers reported normal visual processing in their children. The Face-House task, used to investigate face categorization, was administered in all children. The Face-Emotion task, used to investigate emotional face processing, was administered only in the 10-month-olds and 3-year-olds.

2.2. Stimuli

For the Face-House task, used to investigate face categorization, stimuli were coloured pictures of six female and six male models with a neutral expression selected from the Radboud Faces Database (females identities: 12, 22, 26, 27, 37, 61; males identities: 7, 15, 25, 36, 49, 71; Langner et al., 2010) and 12 coloured pictures of houses selected from internet. For the Face Emotion task used to investigate emotional face processing, stimuli were the same models as in the Face-House task, but now posing once with a happy and once with a fearful expression. The stimuli were depicted on a grey background (RGB: 108) and measured 20.5 cm width x 22.5 cm height (visual angle: 19.4° x 21.2°). During the inter-stimulus intervals (ISI), infants saw a 5.3 × 5.3 cm square in the middle of the screen, which was composed of four coloured squares (red, yellow, blue and green; visual angle: 4.7° x 4.7°).

2.3. Procedure

During the study, children sat either on their parent's lap or on a highchair, positioned approximately 65 cm away from a 23-inch computer monitor (resolution 1920 × 1080 pixels). The testing room was semi-dark. Parents were given instructions not to interact with their children during the experiment. Participants passively observed trials featuring images of faces displaying a neutral expression or images of houses (in the Face-House task) followed by faces displaying a happy or fearful expression (in the Face Emotion task). As described on https://www.uu.nl/en/research/youth-cohort-study, trial duration was 1000 ms, with a jittered ISI between 700 and 1000 ms. The total number of trials per task amounted to 96: for the Face-House task, this included 48 trials for the neutral face condition (4 × 12 models); and 48 for the house condition (4 × 12 houses); for the Face Emotion task, this included 48 trials for the happy face condition (4 × 12 models); and 48 in the fearful face condition (4 × 12 models). Per task, the presentation order of stimuli followed a pseudo-randomized pattern: within each block of 24 trials (4 blocks in total), all images appeared once in a randomized order. Between blocks and during periods when the participant was not looking at the screen, the experimenter introduced additional sounds or video clips aiming to regain the participant's attention. Each task took approximately 3–4 min to complete.

2.4. EEG recording

We recorded continuous EEG data using a 32-channel ActiveTwo BioSemi system (Amsterdam, Netherlands). The offset of electrodes remained under 20μv. The EEG data were recorded with reference to common mode sense and driven right leg (CMS/DRL) electrodes, which were positioned near Cz. The continuous EEG was sampled at a rate of 2048 Hz.

2.5. EEG preprocessing

Data were pre-processed using Matlab (The Mathworks, Natick, MA) and Fieldtrip (Oostenveld et al., 2011). Data were re-sampled offline to 512 Hz, and filtered with a high-pass filter of 0.1 Hz (24 dB/oct), a low-pass filter of 30 Hz (24 dB/oct) and a notch filter of 50 Hz. In order to compute ERPs, epochs of 100 ms pre-stimulus (baseline) until 1000 ms during-stimulus were extracted from the continuous data. The data were demeaned, with baseline defined as 100 ms pre-stimulus until stimulus onset. Trials were removed in single electrodes if it contained artefacts. Artefacts were defined as too high amplitudes (below −200 or above 200 μV); jumps (detected using ft_artifact_jump); excessively

* Note that since our pre-registration, some findings hint towards alterations in the activity of the fusiform face area due to experiences during the lockdown (Yates et al., 2023), which possibly may imply an impact of Covid-19 related policies on face categorization.

† In our pre-registration, we did not specify which expression would be most affected. However, based on a study published after the pre-registration (Wermelinger et al., 2022a), we now specify to primarily expect effects on fearful face processing.

non-normal (kurtosis >7); containing flatlining electrodes (inverse of variance > 0.1) or containing excessive noise (variance > 1500) and absence of data. An electrode was rejected if it contained less than five artefact-free trials in total. Trials were removed in all electrodes if more than 16 % of electrodes contained artefacts as described above (based on previous research on face processing in infants, e.g. Halit et al., 2003; van den Boomen et al., 2019). Activity was then rereferenced to the average of all included electrodes. For each stimulus condition an average of the ERP was created per participant. Electrodes of interest were P7, P3, PO3, O1, Oz, O2, PO4, P4 and P8 (for the N290 and P400) and Cz, Fz, C3, C4, F3, F4, FC1, and FC2 (for the Nc). Based on previous research in infants (Kobiella et al., 2008; Leppänen et al., 2007), participants were included in data analyses for a specific wave if at least 10 segments per condition were included in the individual average of each of the electrodes of interest.

2.6. ERP component analyses

For all components, we investigated the mean activity. The time window for this activity was determined per age-group, because the latency of the components might differ between age-groups. The time window was based on the grand average of all participants in the age-group, and defined as starting at the timepoint half-way the previous component and the current component and ending at the timepoint half-way the current and the next component. For the 5-month-olds, the N290 was computed from 168 to 297 ms, the P400 from 297 to 443 ms, and the Nc from 326 to 574 ms. For the 10-month-olds, the N290 was computed from 168 to 326 ms, the P400 from 326 to 518 ms, and the Nc from 336 to 522 ms. For the 3-year-olds, the N290 was computed from 168 to 326 ms, the P400 from 326 to 518 ms, and the Nc from 320 to 527 ms (See SI2 for a discussion on the time windows). We also extracted the peak latency for the N290 component in response to faces (separately for each expression) in all age-groups by identifying the most negative amplitude within the time window of 168 m to 326 ms (window based on grand averages and visually checked for a random selection of participants), and extracting the latency of this point.

2.7. Statistical analyses

To study speed of face processing at the N290 component, we focused on the latency of the face-evoked N290 component for any face (collapsed across emotions). Due to the not normally distributed data, we applied non-parametric analyses. First, we used the adjusted rank transform test (ART; Leys and Schumann, 2010) combined with a univariate ANOVA to investigate an interaction between Age (5 m; 10 m; 3 y) and Covid group (tested pre; during policies) on N290 latency. Any follow-up analyses would focus on the potential main effects of Covid-19 related policies. Therefore, per age-group we would compare children tested before versus during the Covid-19 related policies.[‡]

To investigate face categorization, we focused on the mean amplitude evoked by neutral faces versus houses. We ran repeated measures ANOVAs using a cross-sectional 3x2x2 design, with Age (5 m; 10 m; 3 y) and Covid group (tested pre; during policies) as independent between-subject variables; Stimulus (face; house) as independent within-subject variable; and amplitude of the ERP (separately for N290; P400; and Nc) as dependent variable.

Finally, to study emotional face processing, we focused on the mean amplitude evoked by neutral, happy, and fearful faces. We used a cross-sectional 2x2x3 design in repeated measures ANOVAs, with Age (10 m; 3 y) and Covid group (tested pre; during policies) as independent between-subject variables; Stimulus (happy; fearful; neutral) as independent within-subject variable; and amplitude of the ERP (separately for N290; P400; and Nc) as dependent variable.

Additionally, we conducted several analyses that are reported in the supplementary information. This includes the pre-registered analyses on the N290 peak (instead of mean) latency and amplitude in three-year-olds (SI4); potential effects of the stringency and duration of the Covid-19 related policies (SI5 and SI6); factors unrelated to Covid that could affect the data quality and might differ between the cohorts (SI7); and sex differences (SI8).

3. Results

Throughout the results section, all outcomes including Covid-group effects are summarized in the text, tables, and figures. Other outcomes on Stimulus and Age-group are reported in the supplementary information SI3.

3.1. Speed of face processing at the N290 peak

The univariate ANOVA revealed a significant interaction between Age and Covid-group ($F(5926) = 12.2$, $p < .001$, $\eta^2 = .062$). Post-hoc analyses showed that for the 5- and 10-month-olds, the distribution of latency between Covid-groups did not differ significantly (all $p > .1$; median latency 5 m pre-Covid: 250 ms; 5 m during Covid: 238 ms; 10 m pre-Covid: 260 ms; 10 m during Covid: 260 ms). However, for 3-year-olds, there was a significantly earlier latency in the during- than pre-Covid group (median latency pre-Covid: 247 ms; during-Covid: 230 ms; Mann–Whitney $U = 8740$, $p < .001$). Fig. 1 presents the box plots, violin plots, and individual data points of all latency results.

3.2. Face categorization

The results from the face categorization analyses are specified in Table 1, and Fig. 2 presents the average ERPs. There were no main or interaction effects of Covid-group on the N290 and P400 amplitudes (all $p > .05$). On the Nc amplitude, there was a two-way interaction between Covid-group and Age-group ($F(2, 924) = 3.155$, $p = .043$, $\eta^2 = .007$). Post-hoc analyses revealed that in the 5-month-old group, infants tested pre-Covid had a larger amplitude (collapsed across stimulus content) than those tested during Covid ($F(1,924) = 5.1$; $p = .024$; $\eta^2 = .005$), while there was no difference between Covid-groups in the 10-month-olds ($F(1,924) = 1.2$; $p = .269$; $\eta^2 = .001$) and 3-year olds ($F(1,924) = 0.2$; $p = .645$; $\eta^2 < .001$). Furthermore, in both the pre- and during-Covid group, 10-month-olds had a larger amplitude than the 5-month-olds and 3-year-olds (all $p < .001$), but the two latter groups did not differ from each other (all $p > .1$). There were no other main or interaction effects with Covid-group on amplitude (all $p > .05$).

3.2.1. Emotional face processing

These analyses only include the 10-month-olds and 3-year-olds; no data on emotional face processing are available in the dataset for the 5-month-old children. The results are specified in Table 2, and Fig. 3 presents the average ERPs and bar graphs. Overall, the analyses revealed several effects of Covid group on emotional face processing: the key findings on emotional face processing include interactions with Stimulus, present at the later ERP components. Below we specify the effects per ERP component, starting with the early N290 component.

N290 mean amplitude – The repeated measures ANOVA revealed a main effect of Covid group ($F(1,568) = 4.938$, $p = 0.027$, $\eta^2 = 0.009$), with a more negative and thus larger amplitude in the during-Covid group. There were no interaction effects with Covid group (all $p > .05$).

P400 mean amplitude – The repeated measures ANOVA revealed a significant two-way interaction between Covid group and Stimulus across age-groups ($F(1.95, 1117) = 3.481$, $p = 0.011$, $\eta^2 = 0.008$; see Fig. 3). Pair wise comparisons to further investigate this interaction

[‡] Note that after submission of the preregistration we noticed that the analyses on N290 peak latency in response to faces were included in the introduction but not in the method section. As we preregistered specific hypotheses on these analyses, we have included them in the 'planned analyses' section.

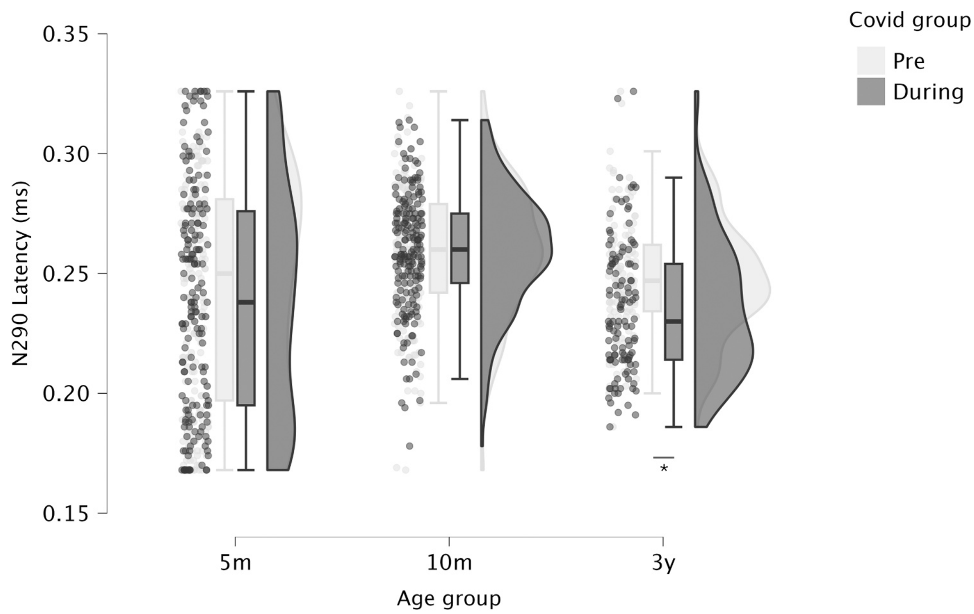

Fig. 1. Individual data points, violin plots and box plots of the N290 peak latency in response to faces, obtained for each age-group and Covid-group. The asterisk below the line linking Covid groups indicates significant statistical differences ($p < .001$). Note that only differences between Covid-groups within each age-group are tested, not differences between age-groups.

Table 1
P-values and effects sizes of interaction and main effects of Covid-group on ERP component mean amplitude in the analyses on Face categorization. Bold results are significant (p < .05). For significant findings, the direction revealed by significant post-hoc analyses is included as well, where the sign (>) indicates which group had a larger (thus more negative Nc) amplitude than the other group. *The non-stimulus specific results are discussed in the supplementary materials.

	Covid-group x age-group x stimulus	Covid-group x stimulus	Covid-group x age-group*	Covid-group
N290	$p = .696$, $\eta^2 = .001$	$p = .118$, $\eta^2 = .024$	$p = .572$, $\eta^2 = .001$	$p = .789$, $\eta^2 < .001$
P400	$p = .560$, $\eta^2 = .001$	$p = .929$, $\eta^2 < .001$	$p = .063$, $\eta^2 = .006$	$p = .862$, $\eta^2 < .001$
Nc	$p = .052$, $\eta^2 = .006$	$p = .653$, $\eta^2 < .001$	$\boldsymbol{p = .043}$, $\boldsymbol{\eta^2 = .007}$ 5 m: Pre > During 10 m: Pre = During 3 y: Pre = During Pre-Covid: 5 m = 3 y < 10 m During-Covid: 5 m = 3 y < 10 m	$p = .755$, $\eta^2 < .001$

showed that in the pre-Covid group, mean activity differed significantly between all facial expressions (all $p < .05$), while in the during-Covid group mean activity did not differ significantly between happy and fearful faces ($p = 0.168$; 95 % CI [-.090,.802]; other emotion comparisons: $p < .001$). When contrasting the Covid-groups, it appears that there was a significantly less positive amplitude evoked by happy faces in the during- than pre-Covid group ($p = .036$; 95 % CI [-1.167, −.040]), while the groups did not differ for neutral or fearful faces (all $p > .1$).

Furthermore, there was a significant two-way interaction between Covid group and Age group (i.e. collapsed across emotional expressions; $F(1, 573) = 4.662$, $p = 0.031$, $\eta^2 = 0.008$). Follow-up pair wise comparisons revealed that within each Covid group, P400 amplitudes were higher in the ten-month-olds than three-year-olds (both $p < .001$; 95 % CI pre [2.254, 3.639]; during [3.332, 4.706]). Yet, within each Age group, P400 amplitudes did not differ significantly between pre- versus during-Covid groups (both $p > .05$; 95 % CI 10 m [-1.029,.209]; 3 y [-.091, 1.417]). Thus, despite the interaction between Covid-group and Age, in each Covid-group the Age-effects were similarly distributed.

Nc mean amplitude - The repeated measures ANOVA revealed only a three-way interaction between Covid group, Age-group and Stimulus ($F(1.935, 1114.3) = 3.571$, $p = 0.03$, $\eta^2 = 0.006$; see Fig. 3). Per Age-group, we further investigated this interaction in two ways: 1) potential differences between expressions for each Covid-group; and 2) potential differences between Covid-groups for each expression. For the 10-month-olds, Covid-groups did not differ. That is, comparison of expressions (1) revealed that neutral faces evoked more negative amplitudes than happy or fearful faces in both the pre- and during-Covid groups (all $p < .001$), and that there was no difference in amplitude evoked by happy versus fearful faces (pre-Covid: $p = .076$; 95 % CI [-.024,.688]; during-Covid: $p = .191$; 95 % CI [-.606,.077]). Further, comparison of Covid-groups (2) showed no group-difference for any of the emotional expressions (all $p > .1$). In contrast, there was a difference between Covid-groups for the three-year-old children. In both Covid-groups, the overall pattern was that amplitudes were more negative as evoked by neutral, followed by happy, followed by fearful faces. However, comparisons between expressions for each Covid-group (1) revealed that in the pre-Covid group fearful faces evoked significantly less negative amplitudes than neutral ($p = .002$; 95 % CI [-1.183, −.199]) or happy faces ($p = .001$; 95 % CI [-1.063, −.266]), while there was no significant difference between neutral and happy faces ($p > .999$; 95 % CI [-.507,.414]). In contrast, in the during-Covid group it was neutral face condition that evoked significantly more negative amplitudes than either fearful or happy faces (both $p < .001$; 95 % CI fearful [-1.301, −.356]; happy [-1.745, −.736]), but the difference between happy and fearful faces was no longer significant ($p = .065$; 95 % CI [-.842,.017]). Comparisons between Covid-groups (2) specified that this seems to be due to a more positive amplitude evoked in the during- than pre-Covid group that was significant for happy faces ($F(1,576) = 7.4$; $p = .007$; $\eta^2 = .013$) but not fearful faces ($F(1,576) = 3.6$; $p = .058$; $\eta^2 = .006$).

Overall, analyses on emotional face processing reveal that for the P400 there was an interaction between Covid group and Stimulus, showing a difference between all emotions pre-Covid, but no difference between fearful and happy expressions in the during-Covid group; which appears to be due to a less positive amplitude evoked by happy faces in the during- than pre-Covid group. For the Nc, there was an interaction

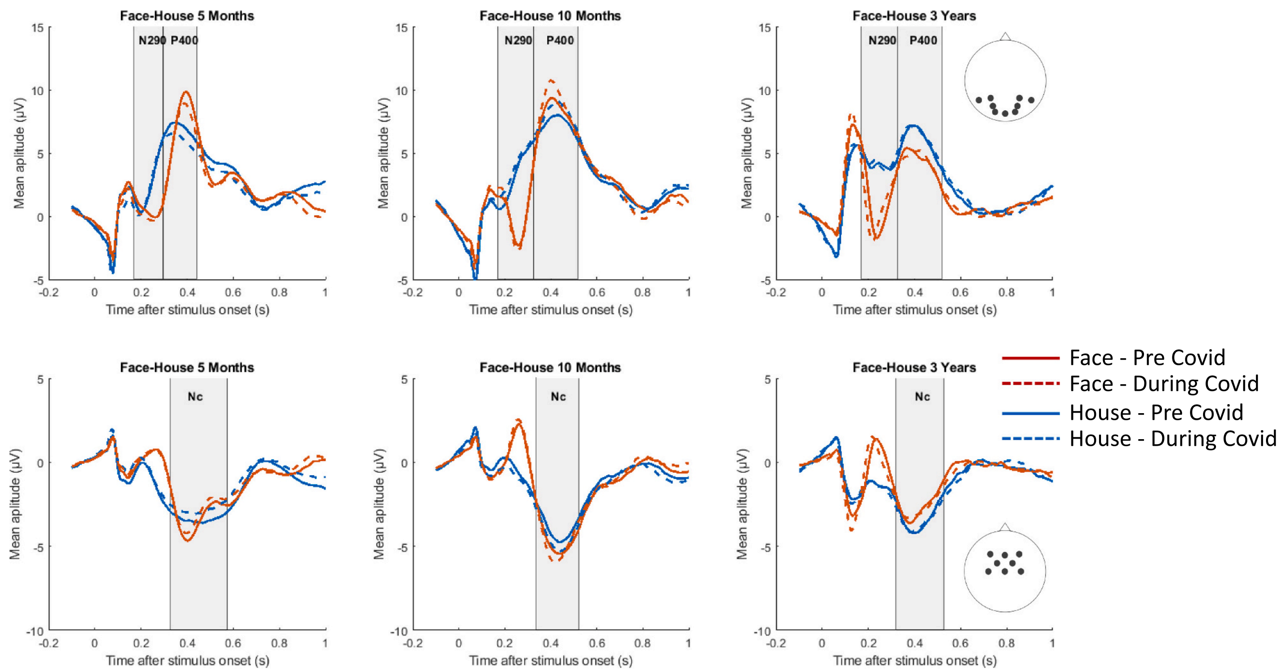

Fig. 2. Average ERPs of responses to faces (red) and houses (blue) evoked in children tested pre (straight lines) and during (dotted lines) the Covid-19 related policies, separately for each age-group and electrode group.

between Covid group, Stimuli, and Age group. There was no Covid-group difference in 10-month-olds, while such effect was present in the three-year-olds, seemingly due to a smaller amplitude evoked by happy faces – and a trend in fearful faces – in the during- than pre-Covid group.

4. Discussion

The current study aimed to investigate the effect of reduced variety of input on three facets of neural representations of face processing in the first four years of life: speed of face processing, face categorization, and emotional face processing. To this end, we compared ERP responses to different stimuli in children tested before versus during the Covid-19 pandemic-related policies. The results show faster face processing, represented by earlier latencies, during versus before the policies in 3-year-olds, but no effects in 5- and 10-month-olds. In addition, there were no effects on face categorization. However, there were substantial effects on emotional face processing: there was a reduced neuro-cognitive differentiation between emotions in children tested during versus before the policies, which seemed to result from a reduced amplitude in response to happy faces, primarily observed in later ERP components and across all tested age-groups. Below we further specify and discuss these results.

4.1. Speed of face processing at the N290 peak

The speed of face processing seems to be affected by experience: in 3-year-olds the N290 peak latency was shorter, representing faster processing, in response to facial stimuli in children tested during compared to before the implementation of the Covid-19 related policies. As reported in the supplementary information (SI4), this effect was face specific as no latency effect was observed in response to images of houses. However, this difference was only present in the 3-year-olds, not in infants. The effects on latency partly confirm the hypotheses, which posited that Covid groups would differ in latency, but that this effect would be most evident in infants. The observed effect on latency in 3-year-olds suggests that reduced experience with faces after the first year of life results in faster face processing.

Previous research investigated effects of input on the speed of face processing using various designs. In studies involving infants, researchers examined ERP responses to faces that participants had extensive experience with (i.e. the mother's face or habituated faces) compared to faces they had limited experience with (i.e. strangers' faces or unhabituated faces). Such studies have shown mixed results, presenting faster, slower, or no difference in ERP responses to experienced faces (Courchesne et al., 1981; Key and Stone, 2012; Luyster et al., 2011; Scott and Nelson, 2006; Webb et al., 2005). Similar designs have hardly been applied in toddlers and pre-school children, except for one study that revealed no effects on the Nc latency (Carver et al., 2003). A more indirect approach suggests that processing speed is faster in children with more experience, as speed increases with development (Di Lorenzo et al., 2020; Kuefner et al., 2010) but not in children that experienced extreme social neglect (Parker et al., 2005). Similarly, indirect evidence in adults suggests that processing speed is faster in controls than in persons that might gain less experience due to social difficulties (McPartland et al., 2004; O'Connor et al., 2005). In contrast, acute effects of reduced input due to masking lead to increased processing speed in adults (Prete et al., 2022). Due to these divergent effects of experience across studies, and the various research designs, the literature shows no clear pattern in the circumstances and age at which input affects processing speed of facial stimuli.

The current results also do not enlighten this pattern further: the presence of effects in 3-year-olds but not younger children suggests that experience is essential for the development of processing speed at this age. This could indicate a version of a critical period for processing speed around three years of age (Pascalis et al., 2020). However, some of the findings in younger children suggest that input is also crucial early in life, although this evidence is based on smaller sample sizes with a larger age-range (Parker et al., 2005) or on contrasting responses to familiar versus novel faces in infants that grow up under typical circumstances (Key and Stone, 2012) and can thus not be directly compared to the current findings. Thus, although the necessity of input for development of processing speed early in life cannot be excluded, the current findings reveal in a large sample that input is crucial around three years of age. Furthermore, face processing was faster, rather than slower, after reduced variety of input. An explanation for this is lacking, and future

Table 2
P-values and effect sizes of interaction and main effects of Covid-group on ERP component mean amplitude in the analyses on Emotional face processing. Bold results are significant ($p < .05$). For significant findings, the direction revealed by significant post-hoc analyses is included as well, where the arrow indicates whether one group had a larger amplitude (in case of N290 and Nc: more negative amplitude; in case of P400: more positive amplitude) than the other group. *The non-stimulus specific results are discussed in the supplementary materials.

	Covid-group x age-group x stimulus	Covid-group x stimulus	Covid-group x age-group*	Covid-group*
N290	$p = .086, \eta^2 = .004$	$p = .074, \eta^2 = .005$	$p = .057, \eta^2 = .006$	$\boldsymbol{p = .027, \eta^2 = .009}$ Pre < During
P400	$p = .123, \eta^2 = .004$	$\boldsymbol{p = .011, \eta^2 = .008}$ Happy: pre > during Fearful: pre = during Neutral: pre = during Pre: neutral > happy > fearful During: neutral > happy = fearful	$\boldsymbol{p = .031, \eta^2 = .008}$ Both pre and during: 10 m > 3 y Both 10 m and 3 y: pre = during	$p = .611, \eta^2 < .001$
Nc	$\boldsymbol{p = .030, \eta^2 = .006}$ 10 m pre: happy = fearful < neutral 10 m during: happy = fearful < neutral 3 y pre: fearful < happy = neutral 3 y during: fearful = happy < neutral 3 y happy: pre > during (pre and during are equal for other emotions and age-groups) Both pre and during: 10 m > 3 y	$p = .163, \eta^2 = .003$	$p = .081, \eta^2 = .005$	$p = .410, \eta^2 = .001$

research should enlighten under what circumstances would input lead to faster versus slower processing speed of facial stimuli.

4.2. Face categorization

In line with our hypotheses, face categorization did not differ between Covid-groups. This corresponds to previous suggestions that the amplitude of ERP components in response to faces is quite stable throughout early life (although individuals differ in their developmental trajectories, particularly at the Nc; Di Lorenzo et al., 2020; Kuefner et al., 2010). The current findings supports the two-process theory of face processing (Johnson, 2005; Johnson et al., 2015). This theory distinguishes between orientation towards faces over objects (referred to as Conspec), which is presumed to be innate, and the developmental process of extracting specific information from faces, such as emotional cues (referred to as Conlern), which supposedly depends on the received input and continues evolving throughout childhood. Based on this theory, face categorization could be assumed to be innate as well: although orienting towards faces over objects (Conspec) does not necessarily equal the (neurocognitive) differential processing of the two items (face categorization), one could assume that Conspec requires face categorization, implying that the latter is innate as well. The current lack of face-specific effect on the amplitude supports that face categorization is indeed possible with limited variety of input.

4.3. Emotional face processing

Emotional face processing differed between children tested before versus during the Covid-19 related policies, particularly at the later ERP components: at the P400 component, children tested before exhibited differential brain activity in response to all three emotions, while those tested during showed no differentiation between happy and fearful expressions. This effect seemed primarily attributed to a reduced amplitude in response to happy faces, and was observed irrespective of age-group. At the Nc component, infants showed no effect of the Covid-19 related policies. In contrast, in 3-year-olds there was once again no differential brain activity between happy and fearful expressions in children tested during the policies, attributed again to a reduced amplitude in response to happy expressions. These findings partly confirm our hypotheses. They support the anticipated decrease in neurocognitive differentiation between emotional faces in children tested during the policies. Nevertheless, we expected these changes to be primarily attributed to responses to fearful expressions, rather than the observed happy ones. Further, our hypothesis on age was only partly confirmed: we expected that Covid-19 related effects would be more pronounced in infants than in 3-year-old children. However, while the effects on both the P400 and Nc components were present in 3-year-olds, there were no effects on the Nc in infants.

The finding that particularly responses to happy expressions were affected in children tested during the Covid-19 related policies could indicate that the development of processing happy faces relies more on a diverse range of input than that of other expressions. This might relate to the development of a face prototype: this is an average face, with variation between individual faces represented on dimensions around this average in a so-called face space. This prototype is supposedly used to encode newly encountered individual faces (Rhodes and Tremewan, 1996; Valentine, 1991). For several aspects of face processing, it has been shown that building and life-long updating of such prototype depends on experience with faces (Burton et al., 2013; Jeffery and Rhodes, 2011; Short et al., 2014). Young children's face space might be more malleable for distortions than that of older children or adults, due to limited prior input (Hills et al., 2010), suggesting that the quantity and quality of input affects the development of the prototype. Applying this to the effects of Covid-19 related policies, it could be suggested that the decreased variety of actors that children interacted with might have hampered the building of a prototype, which consequently hampered the ability to process happy faces. An additional factor contributing to the specific effect on happy expressions might be the specific expressions of those actors that children did interact with. Given the psychological effects of the Covid-19 related policies (Russell et al., 2020; Sperber et al., 2023), we could assume that those actors showed fewer happy facial expressions. The consequent reduced experience with happy expressions might relate to the reported reduced amplitudes in response to such expressions.

Taking a closer look at the specific effects of the policies on processing happy faces, there are reduced amplitudes in later ERP components. This direction of effects (reduced rather than increased amplitudes in response to happy faces) suggests a positive relation between experience and amplitude. The literature also indirectly supports such a positive association between quantity of experience and amplitude: parental and infant characteristics (e.g. increased maternal anxiety) that likely influence the extent of exposure, correlate positively with infant's amplitude in response to an expression related to this characteristic (e.g. fear; Bowman et al., 2022; de Haan et al., 2004; Sandre et al., 2022; Taylor-Colls and Pasco Fearon, 2015). Furthermore, the effects in both previous and current studies might be specifically observed in the later ERP components (the P400 and Nc) due to the neurocognitive processes associated with these components. That is, early ERP components are typically associated with visual perception of the stimulus, while later peaks are thought to relate to attentional allocation to or familiarity with the stimulus (Carver et al., 2003; Conte

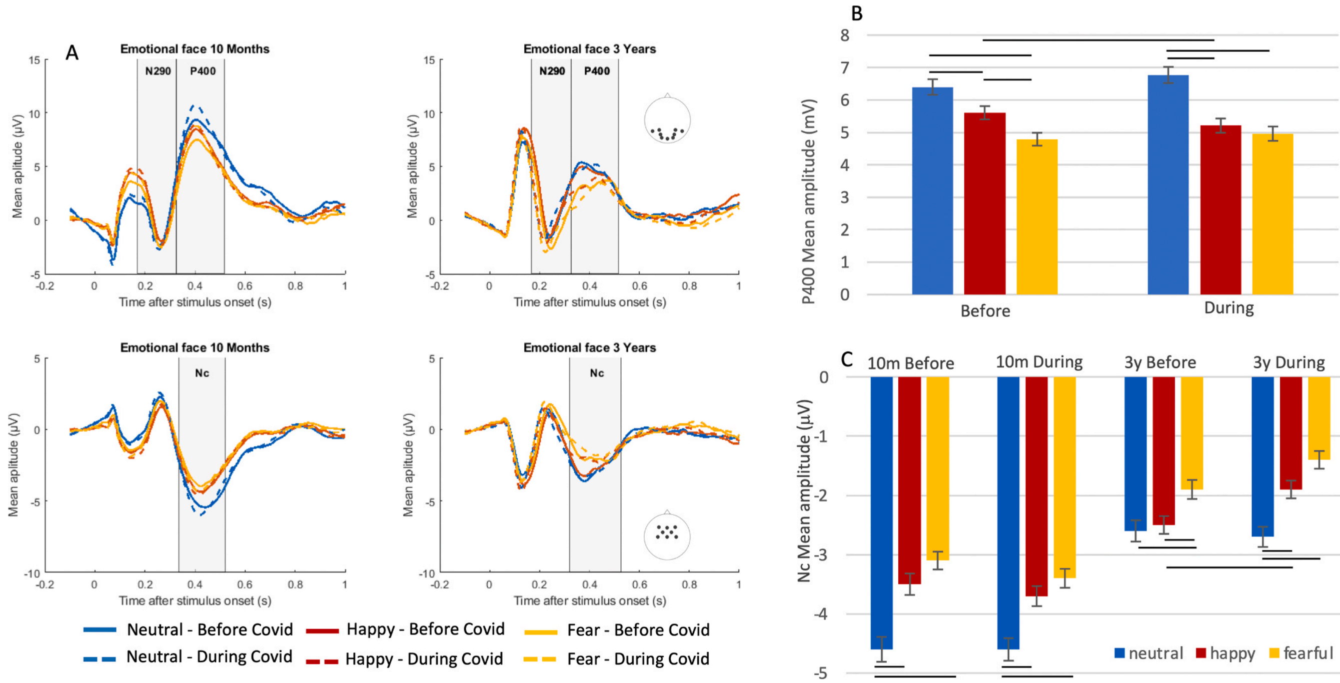

Fig. 3. Average ERPs (panel A), bar graphs of P400 mean amplitude (panel B) and Nc mean amplitude (panel C) in response to emotional faces. **A.** Average ERPs of responses to neutral (blue), happy (red) and fearful (orange) expressions evoked in children tested pre (straight lines) and during (dotted lines) the Covid-19 related policies, separately for each age-group and electrode group. **B.** Averages of responses at the P400 to neutral (blue), happy (red) and fearful (orange) expressions evoked in children tested pre and during the Covid-19 related policies, collapsed for 10-month-olds and 3-year-olds. Error bars represent standard deviations. Black lines represent significant differences between conditions ($p < .05$). **C.** Averages of responses at the Nc to neutral (blue), happy (red) and fearful (orange) expressions evoked in children tested pre and during the Covid-19 related policies, separately for 10-month-olds and 3-year-olds. Error bars represent standard deviations. Black lines represent significant differences between conditions ($p < .05$).

et al., 2020; Glauser et al., 2022). Hence, a reduced amplitude in the later ERP components may indicate reduced attention and/or reduced familiarity with happy facial expressions due to reduced experience.

Furthermore, while we hypothesized that infants would be more affected than 3-year-olds by the Covid-19 related policies, our findings suggest that both infants and 3-year-olds were affected. There might be different reasons for the presence of effects in each age-group: one could speculate that the observed effects could be attributed to how much pandemic circumstances deviated from non-pandemic ones for a particular age-group, combined with the age-related susceptibility of the brain to deviations in input. That is, in non-pandemic circumstances, social interactions become more diverse and complex throughout childhood (Junge et al., 2020), with infants naturally often experiencing a lower variety of input than 3-year-olds. Furthermore, infants show a strong development and thus susceptibility of emotional face processing, while during childhood this ability finetunes (LoBue et al., 2019). The development is contingent to the quantity and quality of input in both 10-month-old infants and 3-year-olds (Leppänen and Nelson, 2009). As such, the effects in 10-month-olds could be explained by a relatively small aberration in variety of input, which had a significant impact due to the high susceptibility. The effects in 3-year-olds could be explained by the relatively large reduction in variety of input, which affected their finetuning of emotional face processing.

Overall, the reduced differential brain activity in response to emotions in children tested during the pandemic aligns with literature highlighting the crucial role of input. Even though the present study did not directly test differences in input, it is reasonable to assume that, for most children, the Covid-19 related policies resulted in a reduced variety of facial input. Previous studies already showed that extreme deprivation (Gao et al., 2013; Parker et al., 2005), as well as characteristics of parents and children (Bowman et al., 2022; de Haan et al., 2004; Sandre et al., 2022; van den Boomen et al., 2021), relate to variations in emotional face processing. In addition, feedback-based training studies in adults revealed similar effects to the current study: specific effects in happy facial expressions, the positive relation between experience and amplitude, and effects on later ERP components (Pollux, 2016). The current study extends the literature by demonstrating for the first time, in a large sample of young children, that rather subtle differences in input have a discernible impact on emotional face processing. The current findings also expand our theoretical understanding of emotional face processing: the effects in both infants and 3-year-olds support the emotional face processing theory (Leppänen and Nelson, 2009), which poses that experience is crucial for the emotional face network to develop. Moreover, the current findings refine this theory: the absence of effects on early ERP components (the N290) suggests that visual processing of emotional faces is not affected by reduced variety of input. The effects on later ERP components in response to happy faces indicates that such deviations in input primarily affect the network's areas associated with stimulus familiarity and attention allocation to a stimulus.

4.4. Limitations and alternative explanations

While interpreting these results, it should be considered that the findings pertain solely to processing of (emotional) faces in the brain, and no direct inferences can be made regarding the behavioural outcomes. This is due to the lack of a behavioural measure of face processing. Nevertheless, both the neuroconstructivism theory (Westermann et al., 2007) and social-first theories (Elsabbagh and Johnson, 2016) suggest that reduced social information processing of an infant could lead to reduced engagement with social stimuli, potentially resulting in reduced or atypical social cognition and communication. It is therefore important to investigate the long-term effects of Covid-related policies on neurocognitive and behavioural outcomes in social competence.

Furthermore, the specific facial input to the children is not included in the current analyses. Although it is reasonable to assume that for most children the Covid-19 related policies resulted in a reduced variety of facial input, differences between children can be expected in the level of reduction and thus the remaining facial input. Such differences could for instance be due to the family situation (e.g. having siblings; parental emotional status before and during the policies), whether children attended daycare, the stringency of the Covid-19 policies (but see SI5 for analyses on this factor, indicating that there is no clear effect of stringency), and the adherence of the parents and children to the policies. Together with factors unrelated to the Covid-19 policies, such as personality of the parent and child, these differences in input could explain variation in face processing between children that participated during the Covid-19 policies. The current study shows that at a group-level, the Covid-19 related policies affected children's face processing, and provides a starting point for future studies that should investigate factors explaining differences in effects between children.

Finally, the interpretation of the results is based on the assumption that the Covid-19 related policies reduced the variety of facial input, and that this reduction is the primary explanation for the observed effects. However, there might be alternative explanations for the observed group differences in processing speed and emotional face processing. First of all, cohort effects (group differences unrelated to the policies) could be due to the timepoint of participation during the day or season (van der Velde and Junge, 2020). As analysed and discussed in SI7, these factors could not explain the current results. Furthermore, several indirect effects of the Covid-19 policies on the (variety of) facial input might have played a role, such as the child's mood that might have affected their interaction with others and consequently the type of input the child received. To our current knowledge, psychological effects of the policies on young children have not been investigated, although negative effects are reported in older children and adults (Chawla et al., 2021; Russell et al., 2020). Together, the current study reveals a difference in face processing between children tested before versus during the Covid-19 related policies. These group differences are interpreted as due to a reduced variety of facial input, but might be more specifically explained by for instance indirect effects of the policies.

5. Conclusions

In conclusion, this large-scale study is the first to reveal a faster face processing in 3-year-olds and reduced differential brain activity in response to emotional expressions in children of 10 months and 3 years tested during the Covid-19 related governmental policies. Furthermore, there was no effect on face categorization. This suggests that a reduced variety of social input negatively affects emotional face processing in both infants and 3-year-olds, and affects the processing speed in 3-year-olds.

CRediT authorship contribution statement

Chantal Kemner: Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition, Conceptualization. **Caroline M.M. Junge:** Writing – review & editing, Conceptualization. **Anna C. Praat:** Writing – review & editing, Formal analysis, Conceptualization. **Carlijn van den Boomen:** Writing – review & editing, Writing – original draft, Visualization, Formal analysis, Conceptualization.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used ChatGPT in order to improve the clarity of some sentences. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the published article.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Chantal Kemner reports financial support was provided by Netherlands Organization for Scientific Research (NWO). If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.dcn.2025.101506.

Data availability

The current data are part of the YOUth study, a longitudinal cohort study of which the Baby & Child cohort follows infants from pre-birth until seven years of age (Onland-Moret et al., 2020). Data can be requested via http://www.uu.nl/en/research/youth-cohort-study.

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