Changes in cognitive effort across infancy and early childhood

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Abstract

Cognitive functioning across development has predominantly been assessed through task performance. However, the role of cognitive effort infants and young children exert has been largely neglected in understanding cognitive functioning. In a large longitudinal sample (YOUth cohort, N = 2241) of infants and young children aged 5, 10 and 36 months, we extracted dynamic baseline-corrected pupil responses to measure cognitive effort during a gap-overlap eye-tracking task. Results revealed a shift from predominantly reactive effort when infants were younger to more preparatory effort in older children, especially for the more demanding condition. Moreover, preparatory effort in infancy predicted cognitive effort in childhood. These findings underscore the importance of measuring cognitive effort in addition to task performance to capture a more complete picture of early cognitive development.

Keywords: Cognitive Effort; Pupillometry; Gap-Overlap Task; Infancy; Cognitive Development.

Introduction

Measuring the emergence of cognitive functioning, like attention and learning, in infancy and early childhood is not only a cornerstone of developmental psychology but also important for early clinical diagnostics and intervention. However, capturing cognitive and attentional functioning in early childhood poses multiple challenges. Developmental trajectories in early life are characterized by sudden and uneven changes across domains, and young children's behavior is affected by situational and affective factors to a much greater degree than that of adults (Ellingsen, 2016). Despite this, most studies on cognitive development remain rooted in experimental designs that focus predominantly on task performance. While such approaches offer valuable insights, they risk overlooking a crucial dimension of development: the effort that children exert while processing stimuli or completing tasks.

The concept of "cognitive effort" remains elusive even after decades of research (Thomson & Oppenheimer, 2022). In this paper, we define effort as an "intensive aspect of attention", in line with Kahneman (1973; see also Kaldy & Blaser, 2020). Studies on adults show that more cognitive effort does not always relate to better task performance (Ackerman & Kanfer, 2009; DeCaro et al., 2011; Thomson & Oppenheimer, 2022). Moreover, "need for cognition", which is an individual's inclination to seek out and enjoy

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cognitive effort, has been linked to more engagement in learning, higher self-efficacy, and higher academic achievements (Liu et al., 2023). Hence, cognitive development should not be assessed only based on differences in performance or skills, but also on the amount of cognitive effort that individuals are willing or able to deploy.

One of the tasks commonly used to test infants' early attentional skills is the gap-overlap task (Hunnius, 2007; Johnson et al., 1991). In this task, a central stimulus is presented for the participant to fixate on it. After participants fixate, a peripheral stimulus appears either before the disappearance of the central stimulus (Overlap condition), after the disappearance of the central stimulus (Gap condition), or at the same time (Baseline condition). Older children consistently disengage faster to look at the target than younger ones (Johnson et al., 1991; Hunnius & Geuze, 2004). Poorer visual disengagement is found in infants who are later diagnosed with Autism Spectrum Condition, and it has been hypothesized as the trigger of negative cascading effects (Elsabbagh et al., 2013; Keehn et al., 2013; Hitzert et al., 2014). However, studies have failed to find clear relationships between performance in the gap-overlap task and other cognitive outcomes (Siqueiros Sanchez et al., 2021; Geeraerts et al., 2019). One reason might be that the measures analyzed in this task have captured performance without looking at individual differences in cognitive effort. Yet, research on adults has shown that it is possible to look at cognitive effort in this task, more specifically at preparatory activity for saccadic planning, using pupillometry data (Jainta et al., 2011).

Pupil dilation has long been associated with cognitive effort (Kahneman & Beatty, 1966): from a biological perspective, the use of pupillometry as a measure of effort can be explained by the link between pupil dilation and the coeruleus-noradrenergic neuromodulatory system (Kaldy & Blaser, 2020; Gilzenrat et al., 2010). In both adults and children, pupil dilation has been related to higher cognitive load and therefore more effort (Hepach & Westermann, 2016; Hepsomali et al., 2019; Wong & Epps, 2016). For example, Chatham and colleagues (2009) found that a transient increase in pupil size was an index of reactive effort, with younger children (3.5-year-olds) displaying more reactive effort than older children (8-year-olds). Kaldy, Guillory and Blaser (2016) assessed memory performance in infants and found that infants whose pupils were larger during the memory-encoding phase had better memory performance on a trial-by-trial basis (Kaldy & Blaser, 2020; Cesana-Arlotti et al., 2022).

In the current study, we investigated how cognitive effort, exerted during the gap-overlap task, evolves between 5 and 36 months of age. By moving beyond task performance and accounting for the effects of potential differences in cognitive effort exerted across ages, we can better understand early cognitive development. We hypothesized that as infants grow older, stimulus-evoked pupil dilation—as an index of cognitive effort—will decrease, since it becomes easier to perform this task. In addition, we tested whether task difficulty (operationalized via the gap, and overlap conditions) increasingly modulates cognitive effort across this age range. Accordingly, we predicted an interaction between age and condition on pupil dilation.

Methods

Participants

The current study analysed data collected as part of the YOUth project (Onland-Moret et al., 2020) and the experimental hypotheses were preregistered (Krol et al., 2024). Here we focus on the eye-tracking data from a gap-overlap task that was collected from 1920 infants at 5 months (mean age of 5.40 months, SD = 0.88; 956 girls), 1823 infants at 10 months (mean age of 10.48 months, SD = 1.10; 893 girls) and 1009 children at 3 years (mean age of 43.50 months, SD = 10.13; 506 girls). In total, 2241 participants were included and most participants took part at multiple time points with an average of 2.12 measurement points per participant. The legal guardians of the infants gave written consent prior to participation and the Medical Ethics Committee of University Medical Center Utrecht approved the study protocol (Protocol ID 14-221).

Procedure

The eye-tracking procedure is described by Belteki and colleagues (2025). The Gap-Overlap task was adapted from Elsabbagh et al. (2009, 2013). In this gaze-contingent paradigm, participants had to switch their visual attention from a central (i.e. cue) to a peripheral stimulus (i.e. target). Figure 1 shows the task design. Each trial began with the cue looming then throbbing in the middle of the screen until the participant fixated on it, which then started spinning for 600-700 ms. Depending on the condition, the cue either remained motionless on the screen (Overlap; Baseline) or disappeared (Gap) for 200 ms. Then a target appeared on the left or on the right (counterbalanced) of the cue. In the Gap condition, the target appeared 200 ms after the cue had disappeared. In the Overlap condition, the target appeared while the cue remained on the screen for another 200ms. In the Baseline condition the target appeared immediately when the cue disappeared. Once the infant/child fixated on the target, it started to either pulsate or spin (combined with a feedback sound) for 1000s. If the participant did not fixate on the target within 2000ms of the onset of the target, the target still started pulsating or spinning. Note that these trials were not included in the analysis. The trials were presented in a random order and on average participants observed 46.4 trials (SD = 13.3).

Preprocessing

We preprocessed the raw data with MATLAB scripts that were developed by the YOUth research team (see Hessels et al., 2019 for data quality checks). We modified these analysis scripts to extract pupil size data. Pupil size data was processed with PupillometryR (Forbes, 2020). First, we regressed pupil size from the left and the right eye against each other and calculated the mean of the two eyes as the final

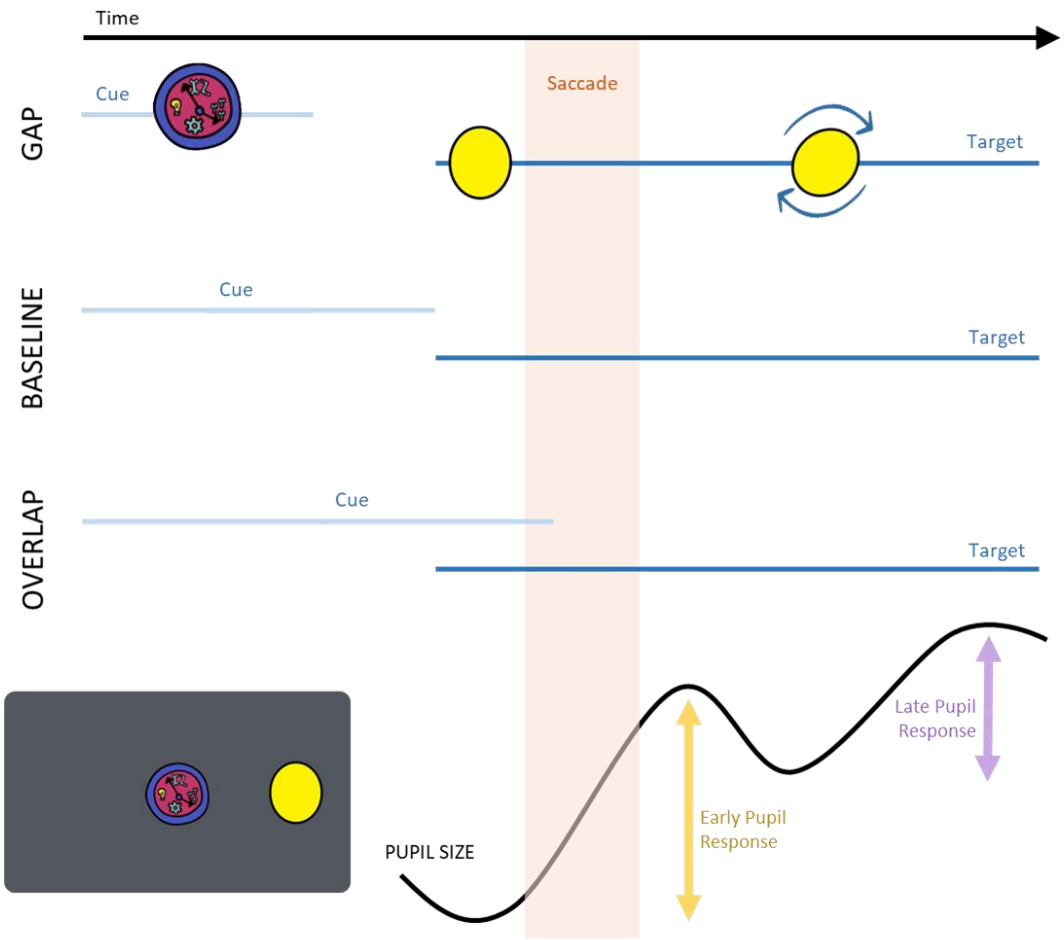

Figure 1: **The gap-overlap task.** The target was presented either 200ms after the cue (Gap condition), the moment the cue disappeared (Baseline condition) or 200ms before the cue disappeared (Overlap condition). After participants looked at the target (Saccade), the target started rotating. Bottom left: the cue was always presented centrally, while the target was presented either on the left or on the right of the screen. Bottom right: pupil size showed an early response, which is related to the effort allocated in preparing the saccade before the target is presented, and a late response, related to effort allocated in preparing a saccade after the target is presented (see Preprocessing).

indicator of pupil size. The data was downsampled to a rate of 20Hz by taking the median of each 50ms time-bin (Mathôt & Vilotijević, 2023). To further ensure the quality of the data, we rejected any trials in which more than 25% of the data samples were missing. This resulted in a trial rejection of 32.4% in relation to the total trial number and a rejection of 24 participants. To reduce noise in the data, we applied a Hanning filter with a degree of 11 samples. Linear interpolation was used to estimate missing pupil size samples to ensure data continuity (Jackson & Sirois, 2009).

Next, we visually inspected the data to determine the best way to baseline-correct the data. In line with previous research (MacLachlan & Howland, 2002), we observed that as age progressed, pupil size increased. In addition, the pupil signal showed two distinct responses - an early response that may reflect preparatory activity (i.e., saccadic planning) and a late response. This is in line with fluctuations in pupil size observed in the gap-overlap task with adult participants (Jainta et al., 2011). Given that these fluctuations were occurring between the cue presentation (which we originally preregistered as the baseline for pupil size) and the target presentation, we opted for a dynamic baseline correction instead. Moreover, modelling the full time-course of pupil data (as preregistered) was computationally very slow and expensive. For this reason, we proceeded with identifying the peak of each trial's responses instead.

For each trial of each participant, we took the minimum value of pupil dilation before a saccade to the target was made (Note that the timing of this minimum value can vary per participant). This served as our first dynamic baseline. Next, we identified the peak value in pupil size, which indexes a preparatory response for saccadic planning (Jainta et al., 2011). Pupil dilation is characterised by a slow response, with a delay of 500 to 1000 ms from the event of interest (van Rij et al., 2019). For this reason, we looked for the peak pupil response within 500 ms after the saccade to the target. Once the peak value in pupil size was identified, we took the difference between this peak value in pupil size and the former minimum value (i.e., the dynamic baseline). In doing so, we obtained a baseline-corrected index of the early pupil response.

Because the initial visual inspection of the data also showed a subsequent pupil response, we replicated the same procedure to identify a second peak in pupil size. First, we identified a minimum value in pupil size following the first peak. Then, we identified a second peak in pupil size defined as the maximum value in pupil size before the end of the trial. Analogously to the initial pupil response, we took the difference between the second peak value and the preceding minimum value to obtain a baseline-corrected index of the late pupil response. While this late response was evident in our data, as well as data from previous studies in adults (Jainta et al., 2011), to our knowledge, it has not been analysed systematically before.

In summary, by devising a dynamic baseline correction for the pupil size data, we obtained two measures of effort. The early pupil response indexes the effort that participants put in planning a saccade before target presentation (i.e., preparatory activity). The late pupil response has not been investigated systematically before, and we hypothesise it might index the effort that participants put in performing a saccade after target presentation (i.e., reactive activity). Together, these measures allow us to explore infants' and toddlers' effort allocation in the gap-overlap task.

Data Analysis

We analysed the early and late pupil responses with Bayesian generalised linear models. The independent variables were experimental condition (Gap, Baseline, and Overlap), age group (5, 10, and 36 months), and their interaction. A random intercept for participants was included. The model was fitted over two chains, with 2000 iterations each (including 1000 burn-in iterations). Skewness-kurtosis plots indicated that all dependent variables were best approximated by a gamma distribution. For this reason, we preferred a gamma distribution to a normal distribution when fitting the data. Effects were interpreted as significant when zero was not included in their 89% credible intervals. These credible intervals are highest posterior density (HPD) intervals, which represent the narrowest interval enclosing 89% of the posterior distribution.

Finally, in an exploratory analysis, we tested whether these measures of preparatory and reactive effort are consistent across development. Specifically, we tested whether the infants' responses at 5 months were predictive of their responses at 10 months, and whether responses at 5 and 10 months were predictive of their responses at 36 months. To obtain a single measure for preparatory and for reactive effort, we subtracted the response in the easiest condition (i.e., Gap) to the response in the hardest condition (i.e., Overlap). This indicates how much more effort infants put in the hardest condition compared to the easiest. We used Bayesian linear models in which measures at previous time-points were used as predictors of the same measures at later time points.

Results

The effects of age and condition on early and late pupil responses are depicted in Figure 2. The early pupil response (i.e., the response that started before target presentation) in the Gap and Baseline conditions was significantly higher for 5-month-old infants (Gap: M = .743, CI = [.735, .751]; Baseline: M = .723, CI = [.715, .731]) compared to both 10-month-olds (Gap: M = .680, CI = [.673, .687]; Baseline: M = .673, CI = [.667, .681]) and 36-month-olds (Gap: M = .671, CI = [.661, .680]; Baseline: M = .672, CI = [.663, .681]). Conversely, in the Overlap condition, 36-month-olds showed the strongest response (M = .631, CI = [.622, .639]), followed by 10-month-old infants (M = .602, CI = [.596, .608]), which in turn showed a greater response than 5-month-olds (M = .587, CI = [.581, .593]).

This pattern of results indicates that 5-month-old infants are putting more preparatory effort for the easy (Gap) and intermediate (Baseline) conditions compared to the other age groups. Conversely, they fail to deploy effort for the difficult condition (Overlap), possibly due to the inability to prepare a saccade while the central stimulus is still present. Ten-month-olds and (even more so) 36-month-olds display more effort in their early response to this more difficult condition.

The late pupil response (i.e., the response that started after target presentation) in all conditions was significantly lower for 36-month-old infants (Gap: M = .069, CI = [.063, .074]; Baseline: M = .073, CI = [.067, .079]; Overlap: M = .071, CI = [.065, .076]) compared to both 10-month-olds (Gap: M = .082, CI = [.078, .086]; Baseline: M = .090, CI = [.085, .095]; Overlap: M = .093, CI = [.087, .097]) and 5-month-olds (Gap: M = .087, CI = [.084, .094]; Baseline: M = .090, CI = [.086, .095]; Overlap: M = .110, CI = [.105, .116]). In addition, it must be noted that in the Overlap condition the response was significantly different for 10-month-olds and 5-month-olds, with 5-month-olds showing the strongest response (M = .110, CI = [.105, .116]).

This pattern of results indicates that reactive effort is deployed more by younger children, especially as the difficulty of the task increases. These results are opposite to what we observe for the preparatory effort, where 5-month-olds deployed the least amount of preparatory effort for the difficult conditions, followed by 10-month-olds and by 36-month-olds.

Finally, we tested the predictive value of pupil responses from earlier to later measurement points. To obtain one measure per age, the response in the easiest condition (Gap) was subtracted from the response in the hardest condition (Overlap). For early pupil responses, 5-month-olds' scores predicted 10-month-olds' scores (b = 0.04, CI = [0.01, 0.7]) and 10-month-olds' scores predicted 36-month-old scores (b = 0.06, CI = [0.01, 0.11]). For late pupil responses, 5-month-olds' scores did not predict 10-month-olds' scores (b = 0.03, CI = [-0.03, 0.10]) and neither 5- nor 10-month-olds' scores predicted 36-month-olds' scores (5: b = -0.07, CI = [-0.20,

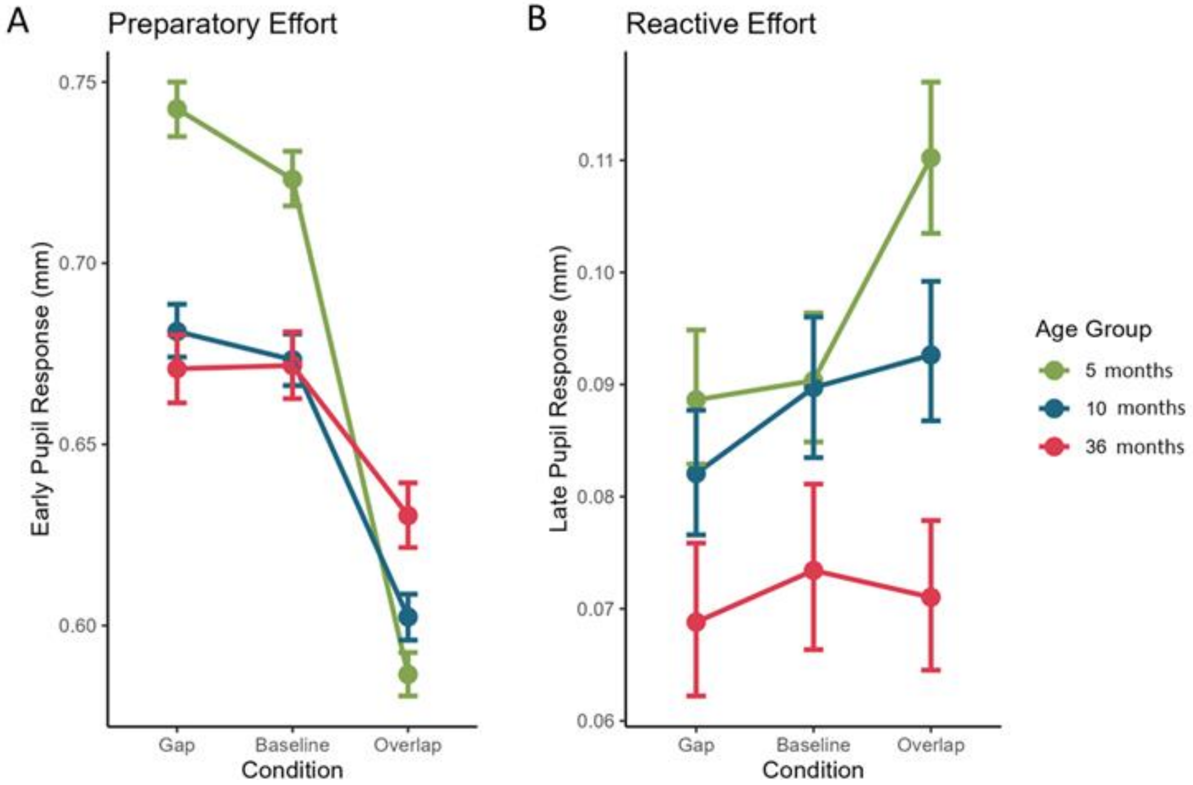

Figure 2: **Early and late pupil responses.** Pupil responses across the three age groups and the three conditions for early pupil responses (A) and late pupil responses (B). Smaller pupil responses reflect lower cognitive effort and larger responses reflect higher cognitive effort. Non-overlapping credible intervals indicate statistical significance.

0.04]; 10: b = -0.08, CI = [-0.16, 0.02]). This indicates that individual differences in preparatory effort are relatively stable from infancy to early childhood, while this pattern was not observed for reactive effort.

Discussion

This study investigated the developmental trajectory of cognitive effort—operationalized via stimulus-evoked pupil dilation—during a gap-overlap task at 5, 10, and 36 months of age. We examined an early and a late phase of the pupil response, which we associate with preparatory effort occurring before or around target onset, and reactive effort occurring after the target appeared. Overall, our results support two main conclusions. First, we observed age-related shifts in how infants and young children allocate preparatory effort: 5-month-olds showed higher preparatory effort in the easier Gap and Baseline conditions, whereas 36-month-olds showed higher preparatory effort in the more demanding Overlap condition. Second, we found that reactive effort was most pronounced in younger children, particularly at 5 months, and gradually diminished by 36 months. These findings suggest that the ability to deploy effort pre-emptively in difficult scenarios develops as infants grow older, and younger infants compensate with greater reactive effort particularly when the task is more challenging.

A similar developmental trajectory in cognitive control has been reported for older children (Chatham et al., 2009), with 3-year-olds showing a qualitatively different reactive form of cognitive control compared to a proactive, adult-like form exhibited by 8-year-olds. Chatham and colleagues (2009) argue that this developmental shift reveals a tendency in the youngest children to react to events only as they occur and a failure to recruit proactive, adult-like parieto-frontal mechanisms in tasks requiring cognitive control. Here, by using a task that did not require any explicit instructions, we extend these previous findings to younger age groups, showing that 3-year-olds already demonstrate substantial improvements in strategically allocating preparatory effort compared to younger infants.

A major strength of this study lies in its large sample drawn from the YOUth cohort, which allows for more reliable group-level results as well as further insights into the longitudinal trajectory of cognitive effort. Additionally, the dynamic baseline-correction method offers a more nuanced approach to handling pupil data in rapidly changing tasks, improving the precision with which we identify stimulus-driven responses. However, two limitations must be acknowledged. First, the relative differences in lighting or screen luminance across conditions may confound pupillary responses. For this reason, the condition differences should be interpreted with caution, and future studies should address between-condition differences as well. Second, while our findings suggest that cognitive effort and performance are distinct constructs, more work is needed to understand the interplay between the two.

Although most developmental studies in infancy focus on task performance (e.g., saccadic latency, frequency of target fixations), our data highlight that pupillometry can capture additional dimensions of behavior—namely the effortful investment that may not necessarily translate directly into performance metrics. Crucially, we find that preparatory effort in infancy is predictive of preparatory effort later, indicating stability in exerting effort when preparing to respond to a stimulus. It also suggests stability in detecting meaningful differences using this new approach to measuring cognitive effort via the gap-overlap task.

Future research could investigate to what extent cognitive effort in infancy can be predictive of later cognitive functioning, from attentional processes to reasoning and decision-making. Extensive longitudinal and meta-analytic evidence shows that effortful control in the preschool and early-school years is a powerful predictor of diverse developmental outcomes (Hernández et al., 2017; Valiente et al., 2011). Higher effortful control forecasts steeper growth in reading, mathematics, even after intelligence and socio-economic factors are taken into account (Hernández et al., 2017). Conversely, low effortful control predicts sharper rises in externalising and internalising symptoms across the primary-school years and is increasingly framed as a transdiagnostic vulnerability factor for a broad spectrum of psychopathologies (Santens et al., 2020).

Crucially, the preparatory effort we measure in infants' pupil response is not necessarily identical to the broader temperamental construct of effortful control: the former is an experimental, task-evoked physiological response, whereas the latter reflects a later-emerging, trait-like capacity for self-regulation typically assessed behaviourally or by questionnaire. Determining whether early physiological effort is a reliable precursor of later effortful control will be an important target for future longitudinal research.

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