Rhythmic visual stimulation as a window into early brain development: A systematic review

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ABSTRACT

Rhythmic visual stimulation (RVS), the periodic presentation of visual stimuli to elicit a rhythmic brain response, is increasingly applied to reveal insights into early neurocognitive development. Our systematic review identified 69 studies applying RVS in 0- to 6-year-olds. RVS has long been used to study the development of the visual system and applications have more recently been expanded to uncover higher cognitive functions in the developing brain, including overt and covert attention, face and object perception, numeral cognition, and predictive processing. These insights are owed to the unique benefits of RVS, such as the targeted frequency and stimulus-specific neural responses, as well as a remarkable signal-to-noise ratio. Yet, neural mechanisms underlying the RVS response are still poorly understood. We discuss critical challenges and avenues for future research, and the unique potentials the method holds. With this review, we provide a resource for researchers interested in the breadth of developmental RVS research and hope to inspire the future use of this cutting-edge method in developmental cognitive neuroscience.

Over 80% of structural brain development takes place in the first years of life (Bethlehem et al., 2022), a period of vast ontogenetic change and unparalleled importance for the developing human mind. Yet, we know astonishingly little about the developing brain during this critical period, mainly due to the challenges in obtaining reliable neural measurements (Hoehl and Wahl, 2012). Rhythmic visual stimulation (RVS) has become a key technique to uncover developmental processes in the human brain. By presenting stimuli at different rhythmic stimulation frequencies, it is possible to induce resonant rhythmic brain responses and to assess these responses in the electroencephalogram (EEG) (Vialatte et al., 2010). This allows researchers to trace the perceptual processing of the presented stimuli and explore the rhythmic dynamics evoked by external stimulation. This approach has been implemented in several modalities, including auditory (e.g., Cirelli et al., 2016) and, most commonly, visual, here termed RVS. RVS is a uniquely useful technique for developmental research due to a clear frequency-specific response for the presented stimuli and its high signal to noise ratio in the EEG. These features make RVS paradigms particularly suited for

developmental populations, where common neuroscience methods (e.g., magnetic resonance imaging [MRI], magnetoencephalography [MEG]) and EEG) reach their limits.

Reflecting its wide and growing application in developmental research, the range of insights that have been gained and the RVS paradigms that have been developed is highly diverse. At the same time, a basic knowledge about the neural mechanisms underlying the RVS response is still missing, such as the effect of different stimulation frequencies and their potential interactions with endogenous brain oscillations. A more profound understanding of these mechanisms is crucial, in particular, if we aim to leverage the unique potential of RVS in studying early brain development. While the RVS method was first applied to understand neural processes in the mature adult brain (Adrian and Matthews, 1934; Herrmann, 2001; see Quigley, 2021 for a review), its merit for developmental research has long been understood. Developmental scientists began to apply RVS in the 1970s, to obtain information about visual processing at a non-verbal age, focusing on the development of visual acuity (Skoczenski and Norcia, 1999; Sokol,

1978), chromatic sensitivity (Allen et al., 1993; Kelly et al., 1997; Kelly and Chang, 2000), contrast sensitivity (Atkinson et al., 1979; Fiorentini et al., 1980; Morrone et al., 1990) and motion sensitivity (Braddick et al., 2005; Hamer and Norcia, 1994). In the past decade, however, the method has been adopted to gain novel insights into early cognitive development, including more complex phenomena as overt and covert attention (e.g., Robertson et al., 2012), face and object perception (e.g., de Heering and Rossion, 2015), numerical cognition (e.g., Libertus et al., 2011), and predictive processing (Köster et al., 2019b). In this context, numerous novel RVS paradigms and analysis techniques have emerged. At the same time, little developmental research has focused on the underlying neural processes elicited by RVS, the effects of different stimulation frequencies, as well as the technical decisions and caveats in analyzing and interpreting the obtained data.

The present review is set out to provide an overview of the state of the field, to reveal open theoretical and methodological queries, and on these grounds to point out critical future directions of the field. Specifically, we describe how RVS has been applied in adults and children, before providing a systematic review of the existing studies applying RVS in the first 6 years of life (using the PRISMA framework; Page et al., 2021), and highlighting important outstanding theoretical and technical issues. We hope that this systematic and critical assessment, which has been missing to date, will provide researchers with guidance when implementing RVS paradigms, foster the awareness of the promise and the possible challenges associated with the RVS method, and thereby advance future research in developmental neuroscience.

## 1. The RVS technique and its application in developmental research

Rhythmic presentation of visual stimuli has been applied in various ways (see Fig. 1 for an overview) and several terms have been used to refer to the method, including (steady-state) visually evoked potentials ([SS]VEPs), frequency tagging, and neural entrainment. These terms do not only reflect the diversity of RVS paradigms, but also diversity in the mechanisms researchers propose RVS induces in the brain. Specifically, 'neural entrainment' refers to the idea that individual brain rhythms can be targeted and experimentally altered by RVS. The term 'SSVEP', on the other hand, suggests a stable repetitive response, not necessarily linked to endogenous oscillatory brain activities. The terms 'frequency tagging' and, more recently, 'fast periodic visual stimulation' (FPVS) have been introduced to circumvent the question of the nature of the neural

response by focusing on the format of the stimulation instead (de Heering and Rossion, 2015; Rossion et al., 2014). Here, we use the term RVS because it is similarly neutral with respect to the assumed underlying neural processes and captures the range of stimulation techniques in the reviewed studies more broadly.

A first study to show that flickering light elicits rhythmic activity in the visual system in adults, as measured with EEG, was conducted by Adrian and Matthews (1934), using photic stimulation (see Fig. 1A). Later, the method was applied systematically, with different stimulation frequencies, in order to better understand the neural responses induced by RVS (Herrmann, 2001; Kamp et al., 1960; Regan, 1975). This research indicated that there is not a one-to-one correspondence between the presented rhythmic stimulus and rhythmic brain activity, but that the brain response differs depending on the stimulation frequency: The neural response (compared to a baseline) is higher in amplitude at some frequencies than at others, indicating a selective frequency preference of the involved neural oscillators. Further, several effects in the harmonics (multiples of the stimulation frequency) were observed. Similar phenomena have been described in subsequent studies (Gulbinaite et al., 2019), which suggests that the RVS response does not only reflect the tracking of a specific visual stimulus, but also leads to resonant phenomena in the brain (Norcia et al., 2015). However, this topic is still intensely debated (e.g., Obleser and Kayser, 2019) and will be discussed in more detail following our systematic review.

A series of studies have also investigated attentional phenomena using RVS, testing how much overt and covert attention a certain stimulus received, as indexed by the RVS response (Martens et al., 2011; Müller et al., 2003, frequency tagging, see Fig. 1D; for studies in infants and children, see Christodoulou et al., 2018; Köster et al., 2017). While these studies did not focus on the specific neural effects elicited by different stimulation frequencies, other studies have employed RVS with the aim to entrain the endogenous neural activity at specific frequencies, in order to associate them with different cognitive functions (Albouy et al., 2022; Clouter et al., 2017; Köster et al., 2019a). Most notably, recent studies tested RVS effects at the 3–8 Hz theta rhythm, reporting enhancing effects of visual stimulation in this frequency range on memory encoding (in contrast to adjacent frequencies; Clouter et al., 2017; Köster et al., 2019a; for a recent review of these and further studies, see Köster and Gruber, 2022). Inspired by this line of work, the targeted stimulation of the theta rhythm has recently also been applied in infancy research (Köster et al., 2019b), as reviewed below.

While most of the foundational research on RVS has been conducted
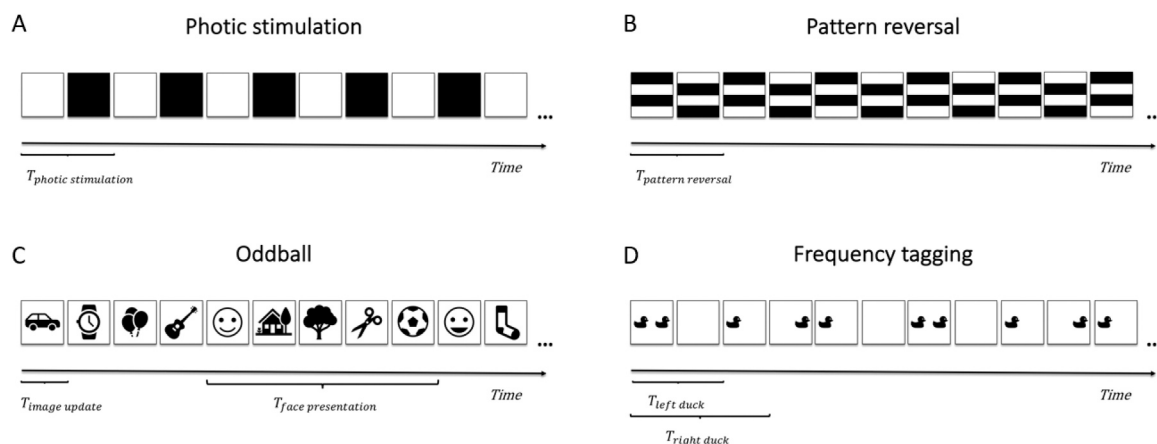
Fig. 1. Schematic graph of the methods using rhythmic visual stimulation. T indicates the period (i.e., 1/f) of a given stimulus presentation. (A) In photic stimulation, luminosity of the entire screen changes periodically. (B) In pattern reversal, stimulus pattern is reversed periodically; this allows introducing changes of the spatial structure without changing the overall luminosity of the stimulus; (C): In oddball paradigms, the image on screen is updated periodically, with the oddball stimulus, e.g., the face, periodically appearing among images belonging to another category, e.g., nonsocial objects. A special use of this paradigm called even-ball involves the presentation of two categories that are equally frequent and alternated. (D): In frequency tagging, two or more stimuli are presented on screen, flickering at different frequencies.

with adults, developmental researchers have taken advantage of RVS in numerous innovative ways. The earliest studies investigated infants' visual acuity using the reversal of black and white checkerboard stimuli at different spatial resolutions (Moskowitz and Sokol, 1980; Porciatti, 1984; Sokol and Dobson, 1976; pattern reversal, see Fig. 1B). This pattern reversal method has often been implemented in sweep VEP designs, whereby an aspect of the visual stimulus is varied sequentially over time (e.g., the spatial frequency of a checkerboard). This allows the determination of the threshold at which the infant visual system does not show a response to the change, yielding an estimate of the visual function of interest (e.g., visual acuity; Almoqbel et al., 2008). More recently, developmental researchers have used fast alternating visual inputs to study the detection of stimuli from a specific category, among stimuli from other categories (stimuli of the target category being repeated periodically, at every *n*th stimulus; oddball method, see Fig. 1C) or the simultaneous presentation of stimuli at different stimulation frequencies, to study the specific processing of one or the other stimulus (frequency tagging, see Fig. 1D). For an in-depth review on different applications of the RVS method, specifically in vision research, see also Norcia et al. (2015).

1.1. Advantages of RVS for developmental neuroscience

RVS is a particularly powerful tool to study human early brain development (see Kabdebon et al., 2022 and Peykarjou, 2022). This is because of the excellent signal to noise ratio in the recorded EEG signal, in contrast to the often-poor signal quality obtained from EEG in developmental populations (Hoehl and Wahl, 2012), due to low trial numbers, high impedances and artifacts due to movement. Another critical advantage of the method comes with the measurement of visual responses to targeted frequencies of specific stimuli, which drastically reduces the search space in the EEG analysis and increases confidence that the obtained response reflects the processing of this stimulus. The robust brain response at a certain stimulation frequency makes the testing of specific hypotheses and therefore the preregistration of infant EEG studies much more viable. The clear association between stimulus and brain response is particularly important for studies applying frequency tagging when distinct frequencies are used for tagging multiple stimuli. This approach allows researchers to ascertain which of two stimuli is preferentially attended when presented simultaneously (Müller et al., 2003; see Fig. 1D). Further, frequency tagging allows the possibility of measuring both overt and covert attentional dynamics, providing information above and beyond overt gaze behavior as assessed in eye-tracking paradigms.

In the following, we will provide a systematic review of the existing developmental RVS research, focusing on the first six years after birth. This period is of high interest for research on cognitive and social development and children in this age range are notoriously difficult to study with conventional EEG/ERP paradigms (e.g., Hoehl and Wahl, 2012) or MRI (Ellis et al., 2020; Lloyd-Fox et al., 2010), and therefore the benefits of applying RVS have been particularly apparent when working with this population. Following our systematic review, we will point out critical caveats and unresolved questions in the application of RVS in developmental populations. These include the neural mechanisms involved in the processing of rhythmically presented stimuli, considerations about the selection of stimulation frequencies, and resonant phenomena, as reflected, for example, in harmonics. Solving these open queries will be essential for the further development of the field and may allow researchers to go beyond contemporary applications of RVS, utilizing the method in yet more sophisticated ways to promote our understanding of the developing human brain.

2. Method

To identify relevant studies, we searched the PubMed database for the following search terms: (fast periodic visual stimulation[Title/ Abstract] OR fast periodic stimulation[Title/Abstract] OR (frequency [Title/Abstract] AND tagg*[Title/Abstract]) OR (steady[Title/Abstract] AND state[Title/Abstract] AND visual*[Title/Abstract] AND evoked [Title/Abstract] AND potential*[Title/Abstract]) OR (steady[Title/Abstract] AND state[Title/Abstract] AND evoked[Title/Abstract] AND potential*[Title/Abstract])) AND (child*[Title/Abstract] OR infan* [Title/Abstract] OR newborn*[Title/Abstract])) AND (EEG OR electroencephalogra*).

We also searched the Web of Science database for the following search terms: (TS="fast periodic visual stimulation" OR TS="fast periodic stimulation" OR TS=(frequency AND tagg*) OR TS= (steady AND state AND visual* AND evoked AND potential*) OR TS= (steady AND state AND evoked AND potential*)) AND TS= (child* OR infan* OR newborn*) AND TS= (EEG OR electroencephalogra*).

This yielded 54 results from PubMed and 83 results from Web of Science, thus a total of 137 results, for which titles and abstracts were retrieved from the databases on 14.05.2020. After removing duplicates, we obtained 107 results. Next, two independent reviewers (ABá and MT, in this and all subsequent steps of the systematic review) screened all titles and abstracts and selected those original empirical papers meeting the following criteria: papers written in English that applied the RVS method in combination with EEG to study early brain development, from any year of dissemination, with methods defined by authors as 'fast periodic presentation', 'fast periodic visual stimulation (FPVS)', 'flickering', 'frequency tagging', 'intermittent photic stimulation (IPS)', 'SSVEP amplitude modulation', 'visually evoked potentials (VEPs)', and 'entrainment' with a stimulation rate faster than 2 Hz (e.g., at least two stimuli presented within a second). We included all age groups between birth and 5;12 years;months, but no unpublished manuscripts or conference abstracts. Thirty-nine out of 107 papers met the above criteria, for which we downloaded the full-texts. Thirty-one papers focused on neurotypical participants and 8 papers were clinical studies. For the purpose of the current review, we decided to focus on non-clinical studies (summarized in Table 1 and the supplementary extended Table S1; a brief overview of the clinical studies which came up in our systematic search is included in the supplementary Table S2).

In a second step, the two independent reviewers carried out a forward search for all the 31 full texts in the same two databases (PubMed, Web of Science) by inspecting the titles and abstracts of all papers citing them. All papers from the forward search that met the above selection criteria were also included in the final set. Inconsistencies between reviewers were solved by discussion. In case a full text was not indexed in either of the databases, we additionally searched Google Scholar for papers citing the original full text and compared the results with those from the respective database(s).

Finally, the two independent reviewers performed backward search by examining the references of the 31 full texts to identify additional papers based on title and abstract that fulfilled the selection criteria. All inconsistencies between reviewers were solved by discussion. Our forward and backward searches resulted in 67 additional full texts: 66 were retrieved between 20.10 and 27.10.2020 from the databases and one was provided by the authors on 04.11.2020. Additional 4 papers were not possible to be retrieved from the databases, or through contacting authors. Fifty-one papers focused on neurotypical participants and 16 papers were clinical studies (see Table S2). The searches led to a combined total of 106 full-text papers to be assessed for eligibility. After inspection, 69 papers were deemed eligible (29 from database search and 40 from citation search) and included in our review. Altogether, 37 papers were excluded (10 from database search and 27 from citation search) due to assessing a clinical participant sample (n = 24), including older age groups (n = 5) or applying a stimulation rate lower than 2 Hz or a non-RVS paradigm (n = 8) (see PRISMA flow digram; Fig. 2).

The articles retrieved for our systematic literature review were screened in detail and entered into a database by the two independent reviewers. Reviewers read the full texts and extracted outcomes and variables according to pre-defined criteria. Specifically, data were
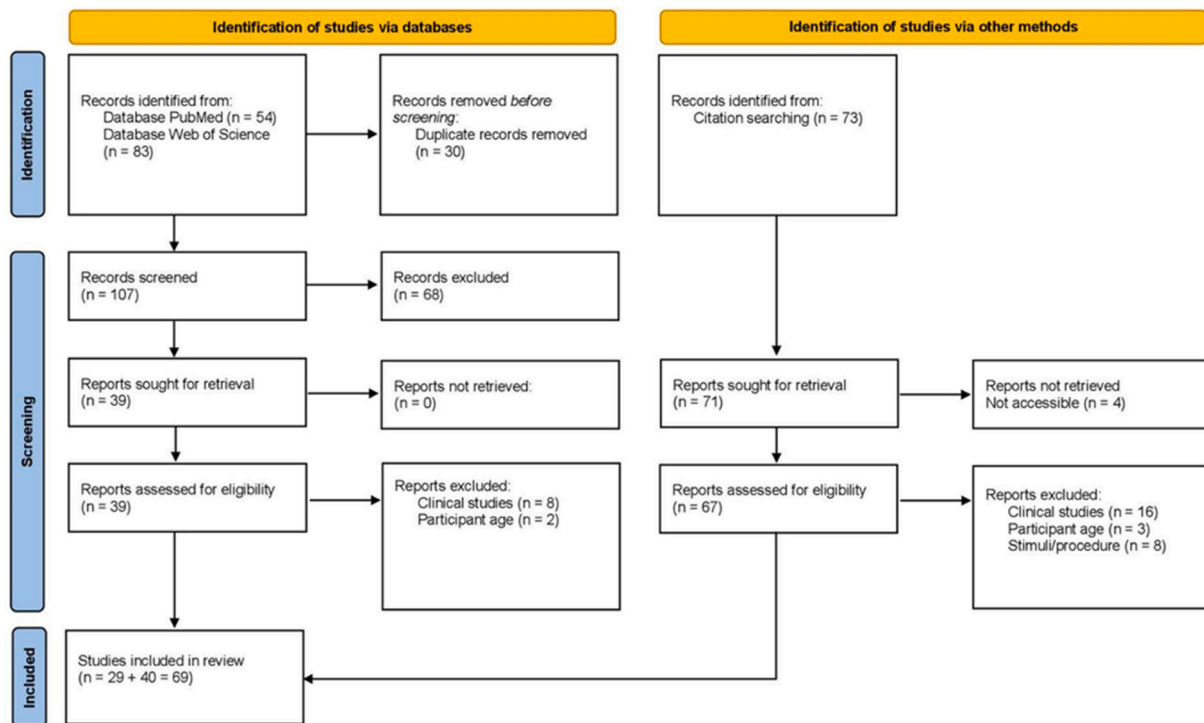
Fig. 2. PRISMA 2020 flow diagram for the systematic review (Page et al., 2021), which included searches of databases PubMed and Web of Science as well as forward and backward citation searching (see main text for more details).

sought for the following outcomes and variables: authors, title, year of publication, digital object identifier (DOI) link, RVS method defined by the original authors, paradigm, number of experiments, topic, further measures, participant age groups, included and total sample size, attrition rate, frequencies used, stimuli type flickered, flickering (e.g., on/ off, sinus), outcome measures, analyzed electrodes, harmonics, number of trials, mean number of trials included in the analysis, trial length, inclusion of participants, inclusion of trial/sequence, open science practices, research aims, empirical findings and the original authors' interpretation of findings. Of all papers, 11.59% (n = 8) were screened by both independent reviewers to establish an agreed-upon procedure, and inconsistencies were solved by discussion. The two reviewers then entered the additional papers individually.

3. Systematic review

Our systematic review of the literature resulted in 69 studies (see Fig. 2). We provide summary of the retrieved papers in Table 1 and an extended version of this table as a searchable database in the supplements of this article (Table S1, as an ".xslx" file). In the following we provide an overview of the insights gained by these studies, beginning with earlier findings on human visual system development to more recent studies investigating the development of higher cognitive functions and studies investigating the neural dynamics elicited by RVS. Substantiating the current dynamic in the field six additional studies fulfilling the search criteria have been published since our initial literature search. We provide these additional studies in Table 2.

3.1. The development of the visual system

The first applications of RVS in developmental vision research focused on measuring visual acuity (Gordon and McCulloch, 1999; Karmel et al., 1974; Skoczenski and Norcia, 1999; Sokol and Dobson, 1976; Suter et al., 1991) and contrast sensitivity (Fiorentini et al., 1980; Fiorentini and Trimarchi, 1992; Kelly et al., 1997; Norcia et al., 1988, 1990; Pirchio et al., 1978). As researchers started to manipulate different aspects of the rhythmically presented visual stimuli, the applications of the method became more diverse, yielding characterizations of various aspects of visual processing, from color vision (Allen et al., 1993; Bieber et al., 1998; Kelly and Chang, 2000; Knoblauch et al., 1998; Morrone et al., 1990, 1993, 1996; Moskowitz-Cook, 1979; Suttle et al., 1997, 2002; Volbrecht and Werner, 1987), through binocular function (Birch and Petrig, 1996; Braddick et al., 1983), to motion perception (Ahtola et al., 2020; Gilmore et al., 2016; Hamer and Norcia, 1994; Mason et al., 2001; Shirai et al., 2009; Wattam-Bell, 1991; Wattam-Bell et al., 2010), orientation and direction processing (Baker et al., 2011; Braddick et al., 1986, 2005; Candy et al., 2001; Hou et al., 2003) and temporal properties of the response to visual flicker (Apkarian, 1993; Moskowitz and Sokol, 1980; Porciatti, 1984).

3.1.1. Visual acuity

One way in which visual acuity has been assessed is by analyzing the RVS response to patterns varying in spatial frequency (e.g., check patterns with varying check sizes) reversed periodically (see Fig. 1B for an example; see Hamilton et al., 2021 for a review which includes child and adult studies). Although visual acuity does not exhibit much change in the first month of life (Atkinson et al., 1979), later on visual acuity develops continuously and becomes almost adult-like at the age of around 8 months (Norcia and Tyler, 1985; Sokol, 1978; Sokol and Dobson, 1976). The RVS response is used as a proxy for acuity based on the fact that the amplitude of adults' RVS response to patterns varying in check sizes is correlated with subjectively reported visual acuity (Harter and White, 1970). Furthermore, the RVS measures of visual acuity in infancy seem to give more accurate estimates than the more traditional method using Teller acuity cards (a tool that tests infants' visual acuity using a forced-choice preferential looking technique), as they are not confounded by the development of neural circuits responsible for producing a behavioral response (Riddell et al., 1997) and the fuzziness in obtaining those measures.

Table 1
Studies included in the systematic review.

Authors	Title	Age Groups	Frequencies	DOI
The development of the visual system				
Visual acuity				
Karmel et al. (1974)	Processing of contour-information by human infants evidenced by pattern-dependent evoked potentials	55–107 days	4.5 Hz	https://doi.org/10.2307/1127747
Sokol and Dobson (1976)	Pattern reversal visually evoked potentials in infants	2–6 months, adults (N/A)	12 Hz	
Sokol (1978)	Measurement of infant visual acuity from pattern reversal evoked potentials	2–6 months	12 Hz	https://doi.org/10.1016/0042–6989(78)90074–3
Atkinson et al. (1979)	Contrast sensitivity of the human neonate measured by the visual evoked potential	1–10 days, 3 weeks, 7 weeks	10 Hz	
Norcia and Tyler (1985)	Spatial frequency sweep VEP: Visual acuity during the first year of life	1–53 weeks, adults (N/A)	12, 14 Hz	https://doi.org/10.1016/0042–6989(85)90217–2
Suter et al. (1991)	Infant and adult grating acuity estimated by VEPs and heart-rate change	10–13 weeks, adults (N/A)	6 Hz	https://doi.org/10.1016/0163-6383(91)90028-Q
Riddell et al. (1997)	Comparison of measures of visual acuity in infants: Teller acuity cards and sweep visual evoked potentials	2–8 months, 3 weeks - 1 year	6.76, 7.5 Hz	https://doi.org/10.1097/00006324–199709000–00017
Gordon and McCulloch (1999)	A VEP investigation of parallel visual pathway development in primary school age children	5-, 8-, 11 years, adults (N/A)	6, 12 Hz	https://doi.org/10.1023/a:1002171011644
Skoczenski and Norcia (1999)	Development of VEP vernier acuity and grating acuity in human infants	2–20 months, adults (N/A)	3 Hz	
Binocular function				
Birch and Petrig, 1996	FPL and VEP measures of fusion, stereopsis and stereoacuity in normal infants	2–8 months, 5–13 years, adults (N/A)	2.5 Hz	https://doi.org/10.1016/0042–6989(95)00183–2
Braddick et al. (1983)	The onset of binocular function in human infants	6–15 days (study 1), 35–100 days (study 2, longitudinal)	3.57 Hz	
Contrast sensitivity				
Pirchio et al. (1978)	Infant contrast sensitivity evaluated by evoked potentials	7-weeks-1 years, adults (N/A)	8 Hz	https://doi.org/10.1016/0006-8993(78)90628–5
Fiorentini et al. (1980)	Scotopic contrast sensitivity in infants evaluated by evoked potentials	2–7 months, adults (N/A)	4–6 Hz (adult only), 8 Hz	
Norcia et al. (1988)	High visual contrast sensitivity in the young human infant	7–11 weeks, adults (N/A)	12, 14 Hz	
Norcia et al. (1990)	Development of contrast sensitivity in the human infant	1–45 weeks, adults (N/A)	6 Hz	https://doi.org/10.1016/0042–6989(90)90028-j
Fiorentini and Trimarchi (1992)	Development of temporal properties of pattern electroretinogram and visual evoked potentials in infants	3–22 weeks, adults (N/A)	1 Hz, 4–8.5 Hz (younger infants), 4–10.5 Hz (17–20 weeks)	https://doi.org/10.1016/0042–6989(92)90154-b
Kelly et al. (1997)	The development of chromatic and achromatic contrast sensitivity in infancy as tested with the sweep VEP	8-, 14-, 20–23-, 32 weeks, adults (N/A)	6 Hz	https://doi.org/10.1016/s0042–6989(97)00011–4
Color vision				
Moskowitz-Cook (1979)	The development of photopic spectral sensitivity in human infants	3–22 weeks, adults (24–29 years)	4 Hz	https://doi.org/10.1016/0042–6989(79)90009–9
Volbrecht and Werner (1987)	Isolation of short-wavelength-sensitive cone photoreceptors in 4–6-week-old human infants	4–6 weeks, adults (23–31 years)	2 Hz	https://doi.org/10.1016/0042–6989(87)90094–0
Morrone et al. (1990)	Development of contrast sensitivity and acuity of the infant colour system	0–40 weeks, adults (N/A)	2–5 Hz	https://doi.org/10.1098/rspb.1990.0116
Allen et al. (1993)	Does chromatic sensitivity develop more slowly than luminance sensitivity?	2–8 weeks, adults (N/A)	3 Hz	https://doi.org/10.1016/0042–6989(93)90134-i
Morrone et al. (1993)	Development of infant contrast sensitivity to chromatic stimuli	0–30 weeks, adults (N/A)	2–5 Hz	https://doi.org/10.1016/0042–6989(93)90133-h
Morrone et al. (1996)	Development of the temporal properties of visual evoked potentials to luminance and colour contrast in infants	6–30 weeks, adults (N/A)	1–30 Hz	https://doi.org/10.1016/0042–6989(96)00050–8
Suttle et al. (1997)	A longitudinal study of visual evoked responses to tritan stimuli in human infants	4 weeks – 3 months (longitudinal study), 7 weeks, adults (29–34 years)	2 Hz	https://doi.org/10.1097/00006324–199709000–00019
Bieber et al. (1998)	M- and L-cones in early infancy: II. Action spectra at 8 weeks of age	8 weeks, 12 weeks, adults (24–43 years)	15 Hz	https://doi.org/10.1016/s0042–6989(97)00384–2
Knoblauch et al. (1998)	M- and L-cones in early infancy: I. VEP responses to receptor-isolating stimuli at 4- and 8-weeks of age	4- and 8 weeks, adults (19–41 years)	7.5 Hz	https://doi.org/10.1016/s0042–6989(97)00383–0

Table 1 (*continued*)

Authors	Title	Age Groups	Frequencies	DOI
Kelly and Chang (2000)	Development of chromatic and luminance detection contours using the sweep VEP	2-, 3-, 7.8-, 8-, 14-, 20-, 32 weeks, adults (N/A)	5.6 Hz	https://doi.org/10.1016/s0042–6989(00)00049–3
Suttle et al. (2002)	FPL and sweep VEP to tritan stimuli in young human infants	1–4 months, adults (<37 years)	4 Hz	https://doi.org/10.1016/s0042–6989(02)00333–4
Form and motion processing				
Braddick et al. (1986)	Orientation-specific cortical responses develop in early infancy	0–9 days, 3–7 weeks (longitudinal)	8.33 Hz	https://doi.org/10.1038/320617a0
Wattam-Bell (1991)	Development of motion-specific cortical responses in infancy	5–20 weeks (motion VEP), 5–16 weeks (eye movements), adults (N/A)	2.08, 4.16, 8.33 Hz	https://doi.org/10.1016/0042–6989(91)90119-p
Hamer and Norcia (1994)	The development of motion sensitivity during the first year of life	7–54 weeks, adults (N/A)	6 Hz (infants), 6, 10 Hz (adults)	https://doi.org/10.1016/0042–6989(94)90283–6
Candy et al. (2001)	Normalization models applied to orientation masking in the human infant	7–26 weeks, adults (N/A)	3.3, 5.5 Hz (test stimulus), 8.3 Hz (mask stimulus)	https://doi.org/10.1523/jneurosci.21–12–04530.2001
Mason et al. (2001)	Directional motion asymmetry in infant VEPs - which direction?	5–21 weeks, adults (N/A)	3.125 Hz	https://doi.org/10.1016/s0042–6989(00)00241–8
Hou et al. (2003)	Development of the spatial organization and dynamics of lateral interactions in the human visual system	8–31 weeks, adults (18–59 years)	2.58, 4.52 Hz	https://doi.org/10.1523/jneurosci.23–25–08630.2003
Braddick et al. (2005)	Motion- and orientation-specific cortical responses in infancy	5–18 weeks	4 Hz	https://doi.org/10.1016/j.visres.2005.07.021
Shirai et al. (2009)	Asymmetrical cortical processing of radial expansion/contraction in infants and adults	3–4 months, adults (mean: 23.6 years)	2.085 Hz	https://doi.org/10.1111/j.1467–7687.2009.00839.x
Wattam-Bell et al. (2010)	Reorganization of global form and motion processing during human visual development	4–5 months, adults (N/A)	2 Hz	https://doi.org/10.1016/j.cub.2009.12.020
Baker et al. (2011)	Orientation tuning in the visual cortex of 3-month-old human infants	3 months, adults (24–52 years)	3.27, 5.14, 8.41 Hz	https://doi.org/10.1016/j.visres.2011.01.003
Gilmore et al. (2016)	Children's brain responses to optic flow vary by pattern type and motion speed	4–8 years	0.6, 1.2, 24 Hz	https://doi.org/10.1371/journal.pone.0157911
Ahtola et al. (2020)	Use of complex visual stimuli allows controlled recruitment of cortical networks in infants	5 months	2, 4 Hz	https://doi.org/10.1016/j.clinph.2020.03.034
Attention				
Robertson et al. (2012)	Attentional dynamics of infant visual foraging	12 weeks	8, 10, 12 Hz	https://doi.org/10.1073/pnas.1203482109
Köster et al. (2017)	Visual cortical networks align with behavioral measures of context-sensitivity in early childhood	5 and 7 years	12, 15 Hz	https://doi.org/10.1016/j.neuroimage.2017.08.008
Christodoulou et al. (2018)	Overt and covert attention in infants revealed using steady-state visually evoked potentials	4 months	6, 10, 12, 15 Hz	https://doi.org/10.1037/dev0000486
Face categorization and individuation				
Farzin et al. (2012)	Piecing it together: Infants' neural responses to face and object structure	4–6 months, adults (N/A)	3 Hz	https://doi.org/10.1167/12.13.6
de Heering and Rossion (2015)	Rapid categorization of natural face images in the infant right hemisphere	4–6 months	1.2, 6 Hz	https://doi.org/10.7554/eLife.06564
Peykarjou et al. (2017)	Rapid categorization of human and ape faces in 9-month-old infants revealed by fast periodic visual stimulation	9 months	1.21, 6.03 Hz	https://doi.org/10.1038/s41598–017–12760–2
Barry-Anwar et al. (2018)	The developmental time course and topographic distribution of individual-level monkey face discrimination in the infant brain	6 and 9 months	1.2, 6 Hz	https://doi.org/10.1016/j.neuropsychologia.2017.11.019
Lochy et al. (2019)	The non-linear development of the right hemispheric specialization for human face perception	5 years	1.2, 6 Hz	https://doi.org/10.1016/j.neuropsychologia.2017.06.029
Leleu et al. (2020)	Maternal odor shapes rapid face categorization in the infant brain	4 months	1, 6 Hz	https://doi.org/10.1111/desc.12877
Lochy et al. (2020)	The right hemispheric dominance for face perception in preschool children depends on the visual discrimination level	5 years	1.2, 6 Hz	https://doi.org/10.1111/desc.12914
Rekow et al. (2020)	Categorization of objects and faces in the infant brain and its sensitivity to maternal odor: further evidence for the role of intersensory congruency in perceptual development	4 months	1, 6 Hz	https://doi.org/10.1016/j.cogdev.2020.100930
Categorization of other visual objects				
Bertels et al. (2020)	Snakes elicit specific neural responses in the human infant brain	7–10 months	1.2, 6 Hz	https://doi.org/10.1038/s41598–020–63619-y
Higher cognition **Numeral cognition**				
Libertus et al. (2011)	Parallels in stimulus-driven oscillatory brain responses to numerosity changes in adults and seven-month-old infants	7 months, adults (20–32 years)	12.5 Hz	https://doi.org/10.1080/87565641.2010.549883

Table 1 (*continued*)

Authors	Title	Age Groups	Frequencies	DOI
Park (2018)	A neural basis for the visual sense of number and its development: A steady-state visual evoked potential study in children and adults	3–10 years, adults (18–23 years)	1, 8 Hz	https://doi.org/10.1016/j.dcn.2017.02.011
Literacy				
Lochy and Schiltz (2019)	Lateralized neural responses to letters and digits in first graders	5–7 years	1.2, 6 Hz	http://doi.org/10.1111/cdev.13337
van de Walle de Ghelcke et al. (2020)	Impact of learning to read in a mixed approach on neural tuning to words in beginning readers	6 years	1.2, 6 Hz	http://doi.org/10.3389/fpsyg.2019.03043
Predictive processing				
Köster et al. (2019b)	Visually entrained theta oscillations increase for unexpected events in the infant brain	9 months	4 (theta), 6 Hz (alpha)	https://doi.org/10.1177/0956797619876260
Properties of the RVS response in the developing brain				
RVS frequency				
Moskowitz and Sokol (1980)	Spatial and temporal interaction of pattern-evoked cortical potentials in human infants	7–26 weeks, adults (20–47 years)	1–7 Hz	https://doi.org/10.1016/0042–6989(80)90095–4
Porciatti (1984)	Temporal and spatial properties of the pattern-reversal VEPs in infants below 2 months of age	3–50 days	0.5–8.3 Hz	
Apkarian (1993)	Temporal frequency responsivity shows multiple maturational phases	0–9 months, adults (N/A)	1–64 Hz	https://doi.org/10.1017/s0952523800010117
Birca et al. (2006)	Interaction between the flash evoked SSVEPs and the spontaneous EEG activity in children and adults	3–16 years, adults (mean: 32.6 years)	5, 7.5, 10, 12.5 Hz	https://doi.org/10.1016/j.clinph.2005.10.001
Harmonics				
Sokol et al. (1992)	Development of lateral interactions in the infant visual system	8–26 weeks, adults (N/A)	4 Hz	https://doi.org/10.1017/s095252380000643x
Grose-Fifer et al. (1994)	Temporal tuning and the development of lateral interactions in the human visual system	14–188 days, adults (N/A)	1, 2, 4, 6 Hz	
Pieh et al. (2009)	Maturation of steady-state flicker VEPs in infants: fundamental and harmonic temporal response frequencies	0–20 months, adults (21–54 years)	4.7, 7.5, 12.5, 19 Hz	https://doi.org/10.1007/s10633–008–9145–6
Analyzed components of the RVS response				
Suter et al. (1990)	Steady-state VEP phase stability and acuity in adults and infants	10–14 weeks	6, 7.5 Hz (3 adults)	
Mackay et al. (2003)	Faster and more sensitive VEP recording in children	1-month -13 years, adults (>21 years)	3.89 Hz	https://doi.org/10.1023/b:doop.0000005334.70304.c7
Birca et al. (2010)	Maturation changes of 5 Hz SSVEPs elicited by intermittent photic stimulation	3–16 years, adults (23–41 years)	5 Hz	https://doi.org/10.1016/j.ijpsycho.2010.09.003
Lee et al. (2012a)	Latency measures of pattern-reversal VEP in adults and infants: Different information from transient P1 response and steady-state phase	3.6–79 weeks, adults (16–43 years)	0.5, 1, 1.5, 2, 3, 4, 4.8, 5.35, 6, 6.85, 8, 9.6 Hz (adults), 1, 1.5, 2, 3, 4, 6, 8 Hz (infants)	https://doi.org/10.1167/iovs.11–7631
Lee et al. (2012b)	Orientation-reversal VEP: Comparison of phase and peak latencies in adults and infants	4–79 weeks, adults (16–43 years)	0.5, 1, 1.5, 2, 3, 4, 6 Hz (adults), 1, 1.5, 2, 3, 4 Hz (infants)	https://doi.org/10.1016/j.visres.2012.04.015

Table 2

Relevant studies published after our systematic literature search.

Authors	Title	DOI
Nyström et al. (2021)	Atypical topographical organization of global form and motion processing in 5-month-old infants at risk for autism	https://doi.org/10.1007/s10803–020–04523–2
Poncet et al. (2022)	A neural marker of rapid discrimination of facial expression in 3.5- and 7-month-old infants	https://doi.org/10.3389/fnins.2022.901013
Rekow et al. (2021)	Odor-driven face-like categorization in the human infant brain	https://doi.org/10.1073/pnas.2014979118
van de Walle de Ghelcke et al. (2020)	Developmental changes in neural letter-selectivity: A 1-year follow-up of beginning readers	https://doi.org/10.1111/desc.12999
Wang et al. (2022)	Lexical and sublexical cortical tuning for print revealed by Steady-State Visual Evoked Potentials (SSVEPs) in early readers	https://doi.org/10.1111/desc.13352
Zhang et al. (2021)	Resting state EEG related to mathematical improvement after spatial training in children	https://doi.org/10.3389/fnhum.2021.698367
Bánki et al. (in press)	Communicative signals during joint attention (versus joint whatching) increased neural processing of visual stimuli in 12-month-old infants and their caregivers	no doi availible yet

3.1.2. Contrast sensitivity

Similarly, contrast sensitivity has been investigated in infants typically with the use of sweep VEP, (Fiorentini et al., 1980; Kelly et al., 1997; Norcia et al., 1988; Pirchio et al., 1978). Infant visual contrast sensitivity rapidly improves over the first five months of life and reaches adult-like levels at the end of the first year (Pirchio et al., 1978).

However, for stimuli at low spatial frequencies, contrast sensitivity measured in the RVS response in 10-week-olds resembled that of adults. This led Norcia et al. (1988) to conclude that any apparent improvements in contrast sensitivity observed after the 10th week of life are rather due to the maturation of spatial acuity. Additionally, contrast sensitivity was found to be different for achromatic (black and white)

and chromatic (red-green) stimuli: while the sensitivity to black-and-white contrast was higher in the first eight weeks of life, sensitivity to red-green contrast had a more rapid maturation rate later on, between the eighth and 32nd week of life (Kelly et al., 1997).

3.1.3. Color vision

The RVS method has also been applied to investigate various aspects of color processing (Allen et al., 1993; Bieber et al., 1998; Kelly and Chang, 2000; Knoblauch et al., 1998; Morrone et al., 1990, 1993, 1996; Moskowitz-Cook, 1979; Suttle et al., 1997, 2002; Volbrecht and Werner, 1987). By manipulating the color content of the flickered patterns, it is possible to isolate responses associated with discrimination between different colors. While many insights into the development of infant color vision have been made with the help of other techniques, such as forced-choice preferential looking (for reviews see Bornstein, 2016 and Teller, 1998), RVS-based measures have also allowed researchers to investigate color vision. For example, Morrone et al. (1990) found that infants showed neural sensitivity to chromatic contrast only after 5 weeks of age, after which color discrimination developed rapidly. Interestingly, adult research indicates that flicker frequencies may interact with the color of the stimulus in their effects on the RVS response (e.g., Duart et al., 2021), suggesting that the color of the chosen stimuli should be taken into consideration for study design (see Discussion).

3.1.4. Form and motion processing

RVS has also been used to characterize the development of form and motion perception, two visual functions supported by complementary pathways of cortical processing and thus often studied together (Ahtola et al., 2020; Gilmore et al., 2016; Hamer and Norcia, 1994; Mason et al., 2001; Shirai et al., 2009; Wattam-Bell, 1991; Wattam-Bell et al., 2010). Using stimuli exhibiting changes in motion (e.g., radial expansion, global rotation) at a specified frequency makes it possible to identify cortical responses associated with processing of that motion type. It was observed that the lateralization of the response to motion differed between adults and 4–5-month-old, with infant responses being more lateralized and adult responses rather midline; moreover, while almost all infants showed responses to motion, only half of them showed responses to changes in form (Wattam-Bell et al., 2010). Additionally, RVS has been used to investigate orientation and direction processing (Baker et al., 2011; Braddick et al., 1986, 2005; Candy et al., 2001; Hou et al., 2003). For instance, Braddick et al. (2005) demonstrated that sensitivity to direction reversal (horizontal displacement of checkerboard patterns) develops at around 11–13 weeks, later than sensitivity to orientation reversal (45° or 135° orientation changes of sine wave gratings), which is already present in infants as young as 4 weeks of age.

3.2. Attention

A handful of studies have employed the RVS method to study the dynamics of infant attention (Christodoulou et al., 2018; Köster et al., 2017; Robertson et al., 2012). A paradigm particularly well-suited for this purpose is frequency tagging, whereby two or more objects in the visual field are flickered at different stimulation frequencies with the aim to dissociate brain responses specific to each object. Increased power at the stimulation frequencies is then interpreted as an augmented processing of the specific stimulus (frequency tagging, see Figs. 1D and 3D for examples).

The first study to employ frequency tagging in infants specifically to examine the dynamics of infant visual attending (or, as the authors also called it, visual foraging) was carried out by Robertson et al. (2012). In their first experiment, Robertson et al. (2012) asked whether increasing infants' attention to a flickering object would enhance the RVS response, as an indicator of focused attention. Three-month-old infants were presented with a toy duck with LEDs attached to it, flickering at 8 Hz. The authors found that introducing motion, with the aim to enhance

attention, led to an increase of the 8 Hz SSVEP amplitude in the EEG power spectrum, and was also associated with increased phase locking of the RVS response to the object flicker (measured directly after, not during, the motion). In the second experiment, infant RVS response to non-fixated objects in their visual field predicted their spontaneous overt shifts of attention, as indexed by infants' subsequent gaze shifts towards the toy duck.

Christodoulou et al. (2018) conducted a series of experiments in 4-month-olds to investigate the effect of attention on the RVS response. In their first experiment, they showed that 6, 10 and 12 Hz, but not 15 Hz, reliably generated equally strong RVS response. In the second experiment, the authors showed that RVS response decreased over the course of habituation to the same flickering checkerboard stimulus, and again increased when a new stimulus was presented. In the third experiment, infants were presented with an engaging dynamic video in the center of their visual field, while at the right and left peripheral fields there were two checkerboards. The authors found the RVS responses to the (likely more attractive) 6 × 6 checkerboards to be higher than those to the 4 × 4 checkerboards, regardless of the frequency at which they were flickered, and in the absence of overt attention shifts.

RVS has also been used to examine individual differences and developmental dynamics of the distribution of attention in 5- and 7-year-old children (Köster et al., 2017; see Fig. 3D). The authors measured children's relative focus on an object versus its background in a visual scene. In the 7-year-olds, but not 5-year-olds, RVS responses were closely related to behavioral measures of children's attentional focus, such as how often they mentioned objects versus backgrounds in their verbal picture descriptions. The study demonstrated a concordance between RVS-derived and behavioral measures of attentional mechanisms and how they align throughout development.

The above experiments on attention provide important insights into the dynamics of infants' and children's attention beyond what can be inferred from looking behavior alone, and further establish the validity of the RVS method in attention development research.

3.3. Face categorization and individuation

RVS-based paradigms have also brought significant contributions to the field of face processing in infancy (Barry-Anwar et al., 2018; de Heering and Rossion, 2015; Farzin et al., 2012; Leleu et al., 2020; Lochy et al., 2019; Peykarjou et al., 2017; Rekow et al., 2020), such as the discrimination between faces and objects (de Heering and Rossion, 2015), the discrimination between different individuals' faces (Barry-Anwar et al., 2018) and the role of face orientation in face categorization responses (Peykarjou et al., 2017).

In the first study to apply RVS to examine high-level visual processing in infants, Farzin et al. (2012) tested whether the RVS response was selective to faces and objects in 4–6-month-olds. A group of infants and a group of adults were presented with pairs of images (either two faces or two objects), with the intact and scrambled images alternating at a rate of 3 Hz. Both adults' and 4–6-month-olds' cortical responses indicated a clear differentiation between intact and scrambled images of faces and objects. The topography of infants' RVS response to faces was more similar to adults' than were the responses to objects, which may reflect a more mature processing of faces relative to objects in infancy. This approach allows researchers to conclude that infants are already sensitive to the visual properties of both faces and objects, but does not allow a direct comparison between faces and objects. This comparison is needed if we wish to examine whether infants process images from the same category as alike and differentiate between images from different categories. In order to do this, studies of categorization often present different images periodically on screen at a certain base rate (e.g., at 6 Hz) with a stimulus from a different category shown every *n*th stimulus (e.g., every 5th stimulus is a face, so faces appear at 1.2 Hz). RVS responses to these different frequencies index the detection of the different stimulus categories (Fig. 1C, oddball paradigm; see also Fig. 3B).
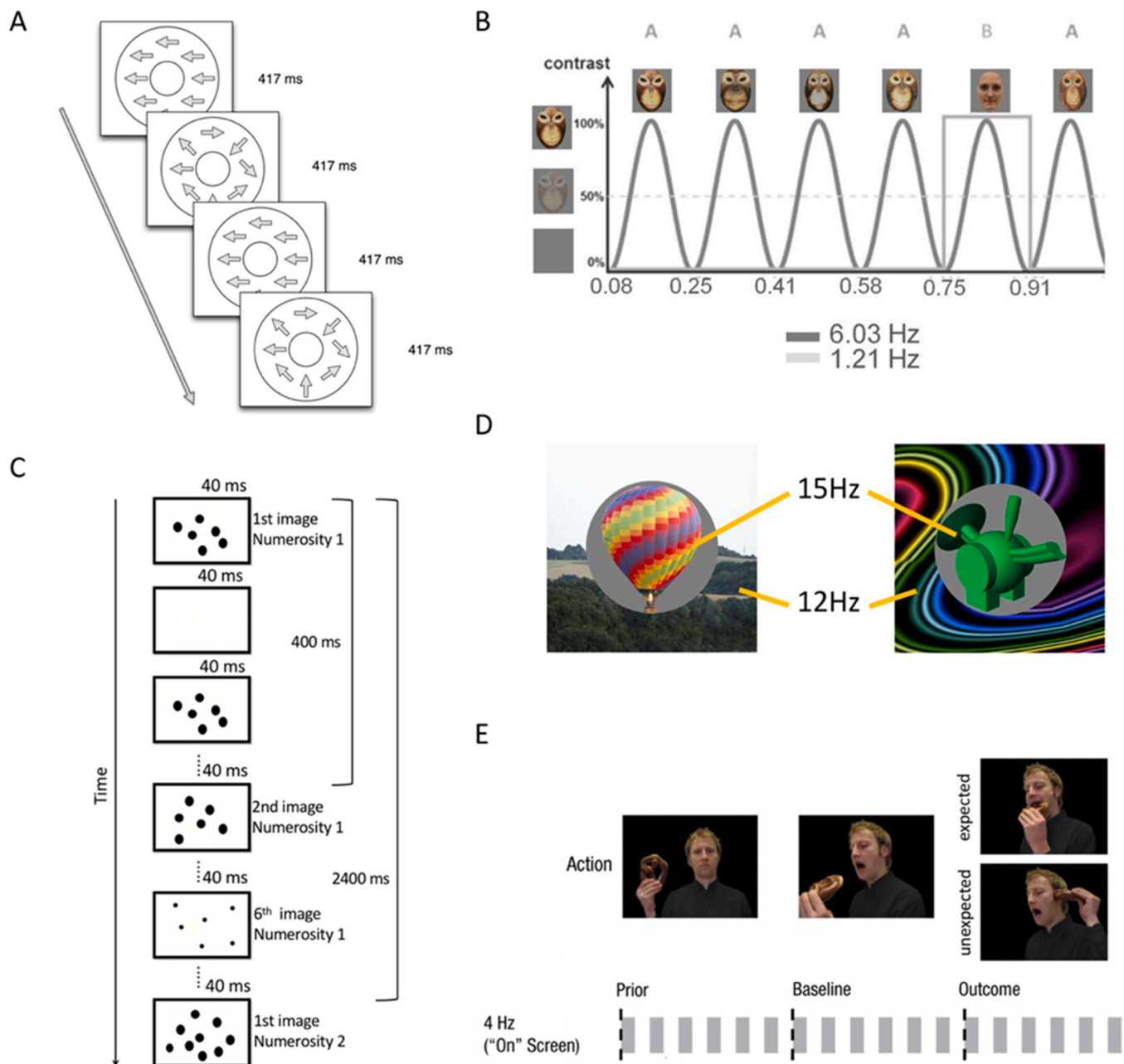
Fig. 3. Exemplary paradigms and stimuli used in developmental RVS research. (A) Motion perception. Stimuli alternated between a coherent phase with rotational global motion versus an incoherent phase at a frequency of 1.2 Hz (from Gilmore et al., 2016, licensed under CC-BY). (B) Face categorization. The image on screen is updated at the rate of 6.03 Hz, with a human face appearing among ape faces at the rate of 1.21 Hz (from Peykarjou et al., 2017, licensed under CC-BY). (C) Numeral cognition. The stimulus was updated on screen at the rate of 12.5 Hz with changes in spatial arrangement and the size of the dots every 0.4 s, numerosity only changed every 2.4 s, allowing for the isolation of a numerosity change specific response when analyzing signal in numerosity-specific blocks (adapted from Libertus et al., 2011). (D) Processing of objects relative to background. By using distinct stimulation frequencies, it was possible to separate bobject- and background-specific neural responses (adapted from Köster et al., 2017). (E) Prediction error in core knowledge domains. Pictures representing events with clearly predictable outcomes (here, examples of action domain knowledge) were visually flickered (e.g., at 4 Hz), with either an expected or unexpected outcome. (adapted from Köster et al. (2019b).

In a first application of this approach with infants, de Heering and Rossion (2015) studied face-selectivity of brain responses in 4–6-month-olds, presenting a series of pictures of objects interspersed with a picture of a face every 5th stimulus. The authors observed a clear right-lateralised brain response to the face stimuli, indicating rapid face detection in the infant brain.

Lochy et al. (2019) found that even though 5-year-olds' face-specific responses were much stronger than those of infants', there was no right hemispheric specialization for faces in this age group. In another study,

Lochy et al. (2020) used varying levels of visual discrimination in the RVS task and found different topographies of responses to the change of face identity versus responses to faces among objects, pointing towards differential mechanisms of face individuation vs. categorization.

Leleu and colleagues (2020) used an analogous paradigm to explore the involvement of the sense of smell in the development of face categorization in infancy. They proposed that the spatial and temporal stability of odor cues could help infants find regularities in their visual environment. Indeed, the authors found that in a condition in which the

mother's worn T-shirt was placed on the infant's upper chest area during the EEG task, the face categorization RVS response over the occipital areas was stronger than the response in a control odor condition (where a clean unworn T-shirt was used). A particularly interesting takeaway from this study is that rapid visual categorization processes can be affected by cues in non-visual modalities.

Several studies employed RVS to compare infant visual processing of human vs. ape faces, testing the emerging experience-dependent specialization of the face processing system for human faces. Pey-karjou et al. (2017) examined the categorization of upright and inverted human and ape faces in 9-month-olds (see Fig. 3B). RVS responses were present for upright and inverted ape faces (among human face standards), as well as for upright human faces (among ape face standards), with the highest oddball response to upright ape faces. The authors concluded that 9-month-olds are capable of rapidly categorizing faces from diverse species, not only humans. Barry-Anwar and colleagues (2018) further showed that 6- and 9-month-olds have the ability to discriminate individual ape faces.

3.4. Categorization of other visual objects

Besides faces, researchers have used the RVS method to study rapid categorization of other visual objects. For example, building on the finding that maternal odor enhances RVS responses to face categorisation (Leleu et al., 2020), Rekow and colleagues (2020) asked whether the olfactory cue could also enhance more generic categorization processes, such as the discrimination between car and non-car objects. While the RVS responses indicated that infants were capable of rapidly categorizing cars among other objects, this was not influenced by whether odor cues were present. In the light of these results, the enhancing effects of maternal odor (Leleu et al., 2020) have been attributed to either a matching mechanism between congruent signals in different modalities, or a specifically social impact of maternal odor (Rekow et al., 2020). In another example, Bertels and colleagues (2020) investigated rapid threat detection in infants and showed that 7- to 10-month-old infants were capable of rapidly detecting snakes among other animals. In two control experiments, the authors found that the oddball response for snakes was higher than that for frogs or caterpillars. This supports the idea of an evolutionarily ancient snake-specific detection mechanism present already in infancy.

3.5. Higher cognition

RVS has recently been applied to study higher cognitive concepts including numeral cognition (Libertus et al., 2011; Park, 2018), reading acquisition (Lochy and Schiltz, 2019; van de Walle de Ghelcke et al., 2020) and prediction error processing within core knowledge domains (action, solidity, cohesion, number) in infancy (Köster, Langeloh et al., 2019).

3.5.1. Numeral cognition

Libertus et al. (2011) tested whether the Approximate Number System, which allows rapid discrimination between non-symbolic numerosities, is active from birth. To address this, Libertus et al. (2011) presented 7-month-olds and adults with images depicting different numerosities, represented by dots in different sizes (see Fig. 3C). Images were flickered at 12.5 Hz; while the size and spatial arrangement of the dots changed rapidly (every 0.4 s), numerosity only changed every 2.4 s (see Fig. 3C), with the new display showing either 1.5, 2 or 3 times as many dots as the previous one. The results showed that in both adults and infants the RVS response was modulated by the ratio of the numerosity change. As such, the study contributed direct evidence for the ontogenetically early emergence of numerosity discrimination. In a subsequent study with 3- to 11-year-old children, Park (2018) showed that the detected effects were specific to numerosity and could not be explained by non-numerosity cues.

3.5.2. Literacy

Lochy and Schiltz (2019) used an RVS paradigm to examine the discrimination between letters and digits in 6-year-olds. Participants watched images rapidly updating on screen, with either a letter appearing among digits, or a digit appearing among letters. The authors found clear categorisation for both stimulus types, and digit-specific responses were right lateralized, while the letter-specific responses were left lateralized. A study into more advanced reading skills (van de Walle de Ghelcke et al., 2020) asked whether neural responses differed when children read words that had been taught to them using different methods. Words had either been taught using the so-called 'global' method of memorising the word as a whole, or the 'letters-speech sounds mappings' method, which requires children to connect letters with the respective speech sounds. The RVS response indicated clear categorization responses for all categories of stimuli, but with differing topographies, suggesting that the cognitive processes elicited by the two methods rely on different neural networks.

3.5.3. Predictive processing in core knowledge domains

Based on the assumption that RVS can entrain internal rhythmic processes and associated functions, in a study by Köster et al. (2019b) with 9-month-olds, the authors found that presenting infants with violation-of-expectation events at the 4 Hz theta rhythm (see Fig. 3E) led to a higher RVS response for unexpected versus expected events. As hypothesized, this was not the case for the stimulation at the 6 Hz alpha rhythm. The authors of the study attributed the discovered effect to neural entrainment of theta oscillations involved in processing new information. This suggests that the frequencies of rhythmic perceptual stimulation employed in RVS studies are differentially modulating infants' endogenous brain activity – a possibility that sheds new light on previous research using the method.

3.6. Properties of the RVS response in the developing brain

Several studies examined the properties of the RVS response in developmental populations, focusing on differential effects of the chosen stimulation frequencies, the phase-stability of the response, harmonics of the response and the underlying components of the SSVEP signal.

3.6.1. RVS frequency

Most developmental studies made use of a small number of predefined stimulation frequencies, without consideration of the specific effects of the chosen stimulation frequencies on the RVS response. However, a small number of studies explored the RVS response in infants as a function of the flicker frequency used (Apkarian, 1993; Christo-doulou et al., 2018; Moskowitz and Sokol, 1980; Porciatti, 1984). For example, Porciatti (1984) set out to test whether structural maturation processes allow infants to process and perceive visual flicker at higher frequencies with increasing age due to the increasing speed of visual processing, which is indeed what they observed. Using stimulation frequencies between 1 and 64 Hz, Apkarian (1993) found that the highest temporal frequency producing a reliable response rapidly increased from ~20 Hz to ~45 Hz in the first 6 months of life, reaching adult-like levels (~59 Hz) by around 9 months of age. However, infants' sensitivity to RVS showed a considerable interindividual variability. Interestingly, in this study, the degree of behavioral arousal (defined by behavioral and eye-tracking measures) predicted infants' neural responsivity to high frequency RVS. A study by Birca et al. (2006) examined the interactions between ongoing brain oscillations during resting state and responses to visual flicker and found no relationship between the flicker frequencies causing the strongest RVS response and the dominant frequencies in resting state EEG. However, they found that suppression of background rhythms induced by RVS pertained specifically to the individual dominant frequencies in resting state EEG, which supports the idea that RVS interacts with endogenous neural oscillators.

3.6.2. Harmonics

When inspecting the spectrum of the RVS response, one can often observe amplitude peaks not only at the frequency of the stimulus, but also at the frequency of its harmonics (e.g., if the stimulus frequency is 4 Hz, second and third harmonics would be at 8 and 12 Hz; Hermann, 2001). The origin of the harmonics has been a subject of scientific debate for many decades (Clynes et al., 1964; Labecki et al., 2016), as a better understanding of the phenomenon is necessary to pinpoint the neural generators of the RVS response. The presence and amplitude of harmonics can be affected by certain properties of the presented stimuli, e. g., asymmetry (Norcia et al., 2015). Relatively little research has analyzed and addressed the topic of harmonics in early development. In one study, it was observed that in young infants, the strength of the second harmonic to asymmetrical stimuli is adult-like weeks earlier than the first harmonic (Sokol et al., 1992). The authors speculated that this may depend on diverging maturational processes of the short- and long-range lateral interactions (Grose-Fifer et al., 1994; Sokol et al., 1992). Another study found that the properties of the RVS response harmonics elicited by light flickering at frequencies between 4.7 and 19 Hz correlate with age, likely indicating visual system maturation (Pieh et al., 2009).

3.6.3. Analyzed components of the RVS response

The interpretation of RVS studies is of course critically dependent on the methods used to analyze the resulting signal. Here, we review several studies that specifically analysed different properties of the RVS response. While in most studies, the RVS response amplitude and signal-to-noise ratio was the measure of interest, Suter et al. (1990) investigated the phase-stability of the RVS response and found that phase-stability is even more sensitive to higher spatial frequencies than amplitude-based measures. Moreover, the phase-based latency of pattern reversal RVS responses has been found to vary with age, likely reflecting the maturation processes in visual cortex (Birca et al., 2010; Lee et al., 2012a, 2012b).

Research has also been done on analysis methods applied to developmental data collected in the basic vision research context. In a computational study, Mackay et al. (2003) found that Laplacian analysis, involving computations of components underlying the RVS response, yielded increased sensitivity and faster RVS detection compared with traditional methods in children aged 1 month to 13 years, meaning that data collection could be even shorter. However, the Laplacian analysis method has not been widely used with developmental data.

4. Discussion

This systematic review documents the diverse ways in which RVS has been applied, showing that RVS has become an impactful tool to study early cognitive and neural development. The advantages of the RVS method for developmental science include the high signal to noise ratio in the EEG signal, and the relatively direct, specific, and unbiased assessment of visual perception and psychological constructs at a neural level. This has led to insights that would not have been possible with other methodologies. Thus far, RVS has been most relevant for our understanding of visual system development, where the method has been applied for many decades. For example, RVS revealed how the infant visual cortex discriminates spatial frequencies, and how visual acuity and color perception develop. However, more recent studies have also demonstrated the method's unique potential for investigating more complex cognitive phenomena, such as overt and covert attention mechanisms, face and object categorization, predictive processing in core knowledge domains, and the targeted manipulation of specific brain frequencies. Thus, RVS comes with the exciting potential to address novel and unique research questions in the decades to come. At the same time, future applications require a more in-depth understanding of the underlying neural mechanisms of the RVS response, to address current limitations and make full use of the method.

4.1. Neural mechanisms underlying the RVS response

Theoretical assumptions about the RVS response vary profoundly between different researchers which impacts their application of the method and their interpretation of results. For example, open questions in the literature concern whether RVS responses reflect stimulus-tracking or entrainment (see Bánki et al., 2022; Keitel et al., 2021) and the role of harmonics. These issues may affect decisions on study design and analysis, depending on the purpose of the study. Thus, advancing our conception of the mechanisms elicited by RVS holds the potential to largely increase the utility of the approach. This may include the targeted manipulation of frequency-specific networks and thereby associated functions throughout development.

4.1.1. Stimulus-tracking

RVS applications like photic stimulation and pattern reversal only rely on the assumption that rhythmic sensory input leads to corresponding alterations in brain activity. The use of frequency tagging of specific stimuli or the fast alternation of visually presented stimuli in oddball paradigms add to this basic assumption that the stimulus is semantically processed (or at least related to higher-level perceptual processes), because the strength of the RVS response is measured and interpreted. These assumptions can be summarized as stimulus-tracking, namely that the neural response tracks the processing of the specific rhythmically presented stimulus.

4.1.2. Entrainment

Much stronger assumptions are made by entrainment accounts, which claim that rhythmically presented stimuli can be used to experimentally manipulate endogenous brain oscillations. The idea that the RVS response interacts with internal operating frequencies is based on relatively broad empirical grounds. This ranges from studies that find differential frequency-specific responses in the brain (see Gulbinaite et al., 2019; Herrmann, 2001 for adult work and Christodoulou et al., 2018; Pieh et al., 2009; Robertson et al., 2012 for evidence that this is similar in early development), to studies which show differential effects of varying stimulation frequencies on cognition and behavior in adults (Albouy et al., 2022; Clouter et al., 2017; Köster et al., 2019b). Thus, there is little doubt that the use of specific frequencies has consequences for interpreting RVS responses. Yet, research on the targeted application of different stimulation frequencies to better understand the interaction with internal operating frequencies is scarce, in particular in the developmental literature. To date, most studies focused on lower frequencies, in the 1–15 Hz (delta to beta) range, see Fig. 4. Therefore, while we know little about the effects of different stimulation frequencies on the RVS responses in adults, we know even less when it comes to developmental populations, where the operating frequencies of the brain may be different (Picton and Taylor, 2007; Saby and Marshall, 2012).

4.2. Harmonics

While relatively little research has been done to understand the sources of RVS responses in harmonic frequencies in the developmental literature, theoretical considerations have been made based on studies with adults. For instance, if the stimulus is sharply changing between 'on' and 'off' luminance states, the harmonics are already present in the input signal (the Fourier spectrum of a square wave contains peaks at the fundamental frequency and its odd harmonics). However, the origin of harmonics has also been attributed to nonlinearities present in the visual system (Labecki et al., 2016), such as the response of the magnocellular neurons to the onset as well as the offset of a stimulus (McKeefry et al., 1996; Norcia et al., 2015).

In some developmental studies, especially in some of the more recent
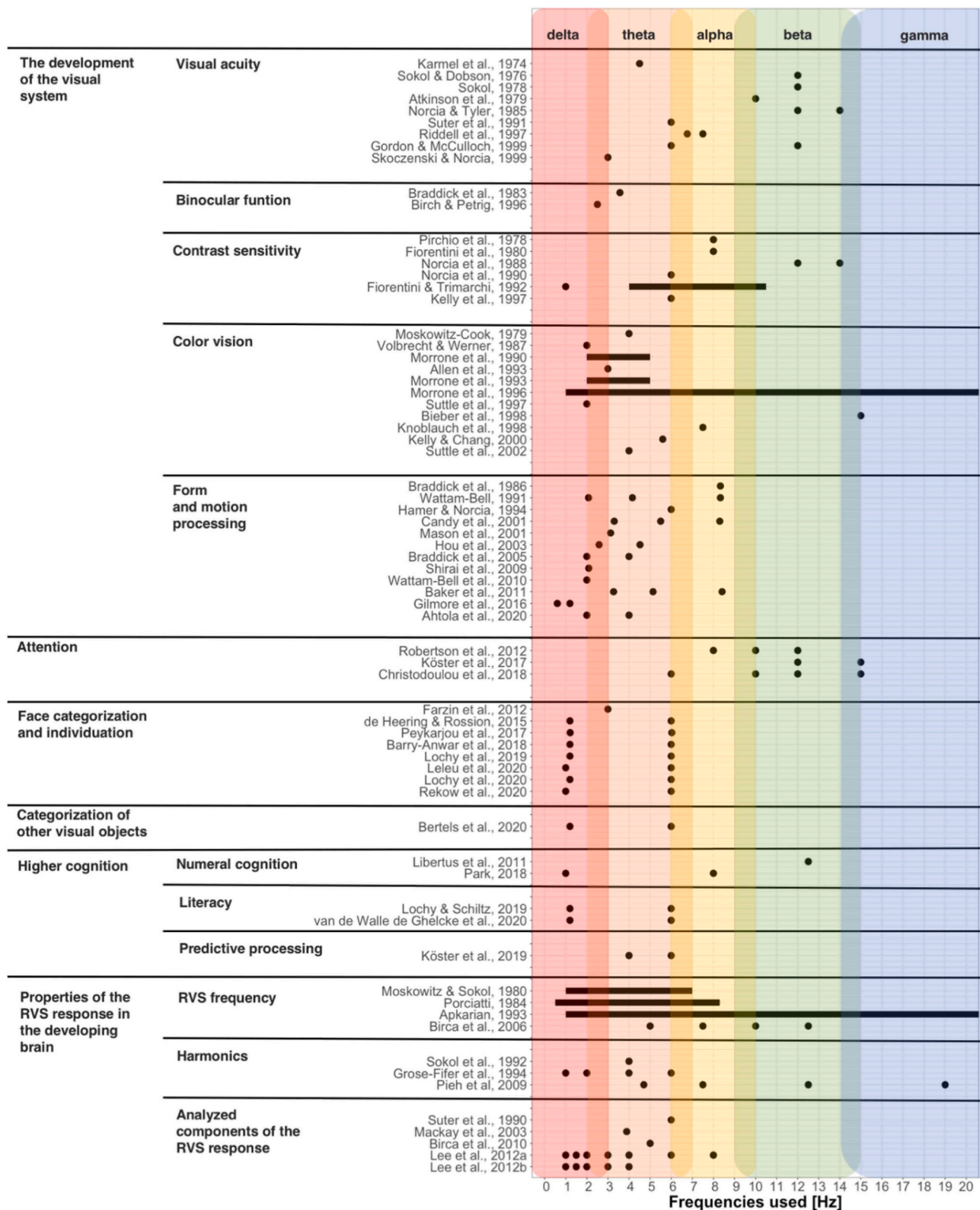
Fig. 4. Overview of the stimulation frequencies used in developmental RVS studies with overlaid EEG frequency bands (note that the frequency band boundaries are not well-defined in the literature and vary across development). Where the authors defined the stimulation frequencies in terms of frequency ranges and the exact values were not given, this is represented in the figure as a solid line covering the defined range. Two studies (Apkarian et al., 1993; Morrone et al., 1996) used frequencies beyond 20 Hz.

ones, the presence of harmonics has been used to 'strengthen' the signal at the frequency of interest by adding up responses at 1 f, 2 f, 3 f etc., without particular attention to the possibly different physiological processes giving rise to the harmonic components of the spectra (e.g., Lochy et al., 2016; Rekow et al., 2020). This approach has been recommended by Retter et al. (2021) as a way of improving the detection of the RVS response of interest. While this practice could be particularly helpful in the context of infamously noisy infant EEG data, it would benefit from more insights into the origins of harmonics, including an understanding of why different stimulation frequencies give rise to harmonics of different strength.

4.3. Methodological considerations

Methodological considerations and analysis strategies critically affect responses elicited and identified in RVS paradigms, and consequently the interpretation thereof (Figueira et al., 2022; Kabdebon et al., 2022). While broader considerations on variations in EEG designs and analyses methods are found elsewhere (e.g., Algermissen et al., 2022; Paul and Mani, 2022), here we will focus on specific considerations for RVS applications.

4.3.1. Stimulation method

One distinction is whether the stimulus content is varied, such as in pattern reversal and oddball paradigms (see Fig. 1B and C), or held constant and is only varied in luminance, such as in frequency tagging and entrainment approaches (see Fig. 1A and D). The former is mostly applied and suitable for change or pattern detection as well as visual categorization, while the latter is mostly used to track the processing of a specific stimulus and the entrainment of neural rhythms. Both methods can be applied using square-wave-modulated signals, such as sharp changes between the stimulus and a gray/black screen (see Fig. 3E), or sine-wave-modulated signals, gradually varying the luminance amplitude (see Fig. 3B). However, for sine-wave-modulated signals the total luminance over single presentation frames is quite hard to control, for example, when effects of different stimulation frequencies need to be considered. An intermediate way is the discrete modulation of stimulus luminance, not switching the stimulus fully off during the "off" screens, but by reducing the luminance to 15 or 20%. This method has been applied to avoid harsh flickering and thereby make the stimulation more appealing and acceptable for young participants (Köster et al., 2017).

Additionally, adult research suggests that the color of the presented stimuli may affect RVS responses. For instance, Duart et al. (2021) showed that while at 30 Hz no differences between RVS responses to white, red and green flicker could be observed, at 5 and 12 Hz the different colors yielded responses of different strength (e.g., higher signal to noise ratio to red and green than to white at 5 Hz). While these effects remain to be studied in infants and children, developmental researchers may want to consider the color of the presented stimuli and possibly counterbalance it across conditions.

4.3.2. Frequency selection

In relation to the neurophysiological underpinnings of RVS, the question of selecting suitable stimulation frequencies arises. One major constraint on this selection is associated with the processing demands of presented stimuli: simpler stimuli can be processed faster, and therefore presented at higher frequencies. This caveat is particularly relevant when the image onscreen changes with every presentation (e.g., in oddball paradigms, Fig. 1C) rather than remaining the same (e.g., in some frequency tagging paradigms, Fig. 1D). While this restriction in RVS paradigms has to an extent been explored in adult research (see e.g., Retter et al., 2018; Retter et al., 2021 for such considerations with regards to face individuation), the results of adult research may not necessarily apply to RVS applications in studying early development, where in most cases it is reasonable to assume that the processing speed would be slower. Indeed, studies done with infants and young children

very rarely made use of frequencies beyond 15 Hz (see Fig. 4). While more fundamental research on the effects of different RVS frequencies is needed and may well be inspired by the recently piqued interest in the method, the choice of stimulation frequencies remains somewhat arbitrary. For specific research questions it is advisable to use previous studies as a reference (see Fig. 4). For example, a frequency combination that is well established for oddball paradigms, is 6 Hz for standards and 1.2 Hz for oddballs (e.g., de Heering and Rossion, 2015). Furthermore, first evidence suggests that one specific frequency that may be suitable to test higher-level cognitive phenomena such as prediction error processing, is the 4 Hz rhythm (Köster et al., 2019b). This selection has been based on functional considerations about the theta rhythm, a rhythm that is particularly preserved throughout human brain development (Cavanagh and Frank, 2014; Köster and Gruber, 2022), and has been found to be involved in cognitive and mnemonic processes in infancy already (Begus and Bonawitz, 2020; Köster et al., 2021).

In frequency tagging paradigms, when presenting stimuli simultaneously, it may be advisable to use adjacent frequencies, which can still be dissociated in the analysis. That is, by choosing neighboring frequencies, it is possible to avoid large differences in the magnitude of the RVS responses, given that lower frequencies commonly elicit stronger RVS responses. At the same time, this strategy prevents harmonics of the lower frequency from interfering with the responses to the higher stimulation frequency (Figueira et al., 2022). Finally, given that RVS may interact with internal brain rhythms, the use of adjacent frequencies, within the same frequency band, may prevent that distinct mechanisms are targeted. For example, in former studies using frequency tagging, frequencies in the alpha/beta range have proven to function well (e.g., 11- and 12-month-olds: 5.67 and 8.5 Hz, in Köster et al., resubmitted; 5- and 7-year-olds: 12 and 15 Hz, in Köster et al., 2017). In any case, it is necessary to counterbalance stimulation frequencies across experimental conditions to avoid confounds, due to different EEG signal strength for different frequencies (e.g., Christodoulou, 2018).

Generally, within the range of typically used stimulation frequencies 1–20 Hz (Fig. 4), lower frequencies may work more reliably than higher frequencies. This is due to lower frequencies being higher in power and less confounded by high frequency artifacts (e.g., muscle activity) and therefore better detectable in the EEG. This holds in particular for developmental populations, where signal quality is reduced, which may be one reason for the clustering of the applied frequencies in the lower ranges (see Fig. 4). This is also underlined by the finding of Christodoulou and colleagues (2018) that a 15 Hz stimulation did not elicit any detectable RVS response in 4-month-old infants; and by an earlier study documenting that the RVS response in the gamma range develops over the first year of life, while still not becoming as reliable as responses to lower frequencies (Apkarian, 1993).

4.3.3. Analysis strategies

Critical RVS analysis aspects are the outcome measure used and the electrodes included in the analysis. Regarding outcome measures, most of the reviewed studies have analyzed the amplitude of the stimulated frequency in relation to the amplitude of the surrounding frequencies (Table 1), referred to as signal to noise ratio. The rationale of this measure is that surrounding frequencies are a reference for the background noise or general activity in a given frequency range. For example, a signal to noise ratio of 1.8, would indicate that the signal at the stimulated frequency is 80% higher compared to the surrounding frequencies or the background noise. This measure, when applied, for example to the results of a fast Fourier transform, is highly sensitive regarding the specific stimulation frequency. Moreover, signal to noise ratios can be tested for significance on the individual level, allowing for research on individual differences and, potentially, being useful in clinical diagnostics.

In cases where the temporal information is relevant, for example when a stimulus varies over time, time-frequency analyses, such as

wavelet convolution or Hilbert transform with a baseline correction (i. e., the difference or relative signal change with regard to a pre-stimulus baseline) may be the method of choice (Hervé et al., 2022). Time-frequency measures have a somewhat reduced frequency resolution (Morales and Bowers, 2022), but this is not very critical since in RVS paradigms the target signal frequency is determined by the stimulation frequency.

Several signal transformations have been used to further improve the detection of the RVS response. Critically, in trial-based designs, it is recommended that the signal for each individual (frequency) condition should be averaged over trials first (i.e., computing the event-related, evoked response; Tallon-Baudry and Bertrand, 1999) before computing the amplitude measure, to unfold the full potential of the RVS approach (Benjamin et al., 2021). As the stimulated signal is stable across trials, averaging across trials levels out the background noise. As outlined in our systematic review, some authors used phase-locking values to directly measure the consistency of the signal over trials (Birca et al., 2010) or applied a Laplacian transformation to improve the RVS detectability (Mackay et al., 2003). Others suggested adding up higher harmonics as a RVS response (e.g., Retter et al., 2021; cf. paragraph on harmonics) to this end. Yet another approach to increase signal to noise ratio rests on the assumption that the stimulated rhythm interacts with endogenous frequencies. In studies where this may be the case or is even the focus of investigation, it may be feasible to select the individual participant's frequency with the highest RVS response (also named preferred resonance frequency, Birca et al., 2006), to further increase the signal to noise ratio (e.g., the stimulated theta rhythm at 4 Hz may lead to a peak response in the individual brain's 3–5 Hz range; cf. Köster et al., 2019b).

The electrodes included in RVS analyses vary largely across studies (see Table 1), ranging from single electrodes to the inclusion of broad clusters. An electrode included in most studies is the occipital Oz, where the RVS response usually peaks. Several studies also include the surrounding occipital channels or broader occipital and parietal electrode clusters. Face-specific responses in oddball paradigms commonly peak at the parietal P8, located just over the fusiform face area. However, the selection of electrodes is not trivial: while the grand mean amplitude reliably peaks at occipital channels, for higher cognitive processes condition-dependent differences in activity may be found in channels over higher-level visual areas, such as the aforementioned P8 electrode for the processing of faces (de Heering and Rossion, 2015), parietal channels for prediction error processing (Köster et al., 2019b), or central and parietal channels for the processing of context versus object information (Köster et al., 2017). The selection of electrodes may also be based on considerations about the visual system, such as the analysis of contralateral electrodes for flicker presented on one specific side of the visual field (see e.g., Christodoulou et al., 2018). For keeping the analysis strategy unbiased by condition effects, large occipital and parietal electrode clusters may be included in the analysis, which also accounts for interindividual topographical differences. A useful tool to pinpoint specific condition differences, not located in the grand mean cluster are cluster-based permutation tests (as in e.g., Rekow et al., 2021; for more details on the approach see Meyer et al., 2021).

In general, the signal to noise ratio may be maximized by testing different ways of analyzing the data and selecting the peak electrodes that reflect the RVS response best. However, it is critical that such an optimization is done prior to the calculation of any condition-specific responses, to avoid biasing any statistical differences. Optimizing signal quality across conditions and selecting peak electrode clusters before splitting data into conditions for analysis allows researchers to get the maximal signal quality out of their specific dataset, without a condition bias. This is a clear advantage of the RVS approach, where the stimulation frequency drastically limits this initial search space. Yet, for the future of the field it may be critical to systematically test for the effects of different analysis strategies (see e.g., Batterink and Choi, 2021; Benjamin et al., 2021), and to be able to provide more general best

practice advice, which is hard to derive given the diversity of analysis methods until to date. Meanwhile, researchers may consider specification curve analysis to identify the consequences of specific analysis decisions and base inferences on results derived across all theoretically justifiable specifications (Simonsohn et al., 2020).

4.4. Limitations

Despite its success and the critical insights gained by the RVS approach, our systematic review and discussion expose many questions that are still unresolved about the effects that RVS has on brain activity and how methodological choices can impact the results obtained in RVS studies. Improving both our understanding and applications of RVS holds great potential for advancing the field and will thereby provide new insights into human brain development.

First of all, while the stimulated signal elicits a strong peak at the stimulation frequency at posterior recording sites, the overall brain response and EEG signal becomes highly obstructed, making it impossible to gain insights into the natural and potentially rhythmic response of the brain towards the presented stimulus content (although in specific paradigms, RVS responses have been analyzed alongside event-related potentials, cf. Kabdebon and Dehaene-Lambertz, 2019). Thus, the RVS approach is most suitable for either testing hypotheses that do not rely on assumptions about internal driving frequencies (e.g., in case of frequency tagging approaches) or focusing on the role of certain frequencies involved in a specific process (e.g., in entrainment studies). Either way, given that the brain's response may interact with specific stimulation frequencies, a profound consideration and piloting of different frequencies prior to the final frequency selection is crucial. As long as we lack a better understanding of how RVS and endogenous brain processes interact (Doelling and Assaneo, 2021), this approach holds the risks of either testing effects that are only visible in a specific frequency range, or, more critically, misses to capture perceptual or cognitive phenomena, due to an unsuitable selection of a stimulation frequency.

Another limitation in RVS paradigms is the interpretation of obtained topographies. While the locus of neural activity and specific topographic effects are already highly challenging to discern in common EEG paradigms, this difficulty increases for RVS paradigms, where the activity peaks sharply at occipital electrodes. Although some contrasts found in former experiments show differential effects at very specific locations (such as electrode P8 in oddball paradigms on face perception; e.g., de Heering and Rossion, 2015; Rekow et al., 2020), difficulties with interpreting topographic differences between conditions may generally be amplified in RVS paradigms.

Additionally, it is sometimes the case that RVS does not elicit reliable neural responses (i.e., SNRs higher than 1.0) in some participants, even in case of stimulation frequencies that reliably work for the majority of participants (see e.g., Christodoulou et al., 2018). This points to the importance of considering individual differences in the RVS response. Hopefully, future research will shed more light on the causes of the lack of RVS response in some participants. There is a good prospect that the increasing popularity of RVS in developmental science will stimulate critical research and discussions on the method and its applications in studying the developing brain. Our systematic review aims to guide researchers in identifying research gaps and appropriate study designs when applying the method. It will hopefully inspire more groundwork promoting a better understanding of the effects that RVS has on the developing brain and thereby help us to optimize RVS techniques in the continued effort to unravel critical aspects of human early brain development.

4.5. Future directions

Despite its caveats, RVS holds the potential to address unique research questions on human early brain development. Given the

enormous creativity in the study designs developed and the research questions addressed, it is impossible to foresee in which exciting directions the field may further develop. Here, we will highlight some outstanding knowledge gaps and potential approaches to address those gaps. Finally, we outline some ideas for RVS applications that may take the insights gained into early cognitive development further.

4.5.1. Understanding the effects of RVS on the developing brain

As discussed above, more research is needed regarding the effects of different stimulation frequencies and the specific neural dynamics elicited in RVS paradigms, as well as the implications of different analysis methods on the results obtained. We know very little on the effects elicited by RVS on endogenous processes in the developing brain. While research in adults suggests that different frequencies elicit different network dynamics (Herrmann, 2001) and that targeting specific frequencies, such as the theta rhythm, can lead to differential behavioral outcomes (Hanslmayr et al., 2019), research into this direction is still scarce. A critical challenge in this regard is that we still lack a profound understanding of how the oscillatory landscape develops across the lifespan. While there is some evidence that the theta and alpha rhythms are already present in the EEG in the first years (Köster et al., 2021; Saby and Marshall, 2012; Stroganova et al., 1998, 1999; Stroganova and Orekhova, 2007), it is suggested that the frequency, locus and magnitude of the theta and alpha rhythm may change over development (Cellier et al., 2021). In fact, cross-sectional and longitudinal studies on the changing dynamics in the RVS response to different stimulation frequencies may be a highly valuable addition to the existing literature and could provide researchers with much more confidence as to which frequencies to apply for RVS. This could be complemented by studies testing the effects of different stimulation frequencies on infant behavior, for a proof of concept that entrainment of cognitive phenomena through visual stimulation is possible at an early age.

4.5.2. Applications to advance our understanding of early brain development

Further groundwork could provide essential insights into early brain development. For example, when do frequency-specific networks develop and how do they change over the lifespan? However, research addressing this question is constrained by the low spatial resolution of EEG measures. Critical methodological advances may potentially help to overcome these limitations, including EEG with complementary (f)MRI assessments to link structural development to the development of network dynamics (Di Russo et al., 2007). This may be facilitated by recent developments in applying fMRI in infants and linking the spatial results obtained in fMRI studies to temporal dynamics in the EEG, for example using representational similarity analyses (Kriegeskorte et al., 2008; Xie et al., 2020). These advances may help to identify and characterize resonant phenomena in the developing brain and thereby explore the emergence of frequency-specific networks. Crucial recent advances in this regard include optically pumped magnetometers (OPM; e.g., Boto et al., 2017), a novel tool to directly resolve temporal dynamics in time and space, similar to MEG, which may facilitate applications in developmental populations in the future.

4.5.3. Neurocognitive assessments and enhancement

An exciting future avenue is the development of neurocognitive assessments based on RVS methods, for example, to probe early visual system development or measure infant capacities to attend to and entrain to certain external pacemakers to establish an early marker of neural functioning (Lalancette et al., 2022). Future developments in the field may enable the application of RVS in learning contexts for cognitive enhancement by making the method less intrusive. These approaches include, e.g., using stimuli varying only slightly in luminance or high-frequency visual flicker invisible to participants (rapid-invisible frequency tagging, Brickwedde et al., 2022). Another application could be to use RVS to guide and stimulate attention networks to treat attention deficits. A particularly promising avenue in this regard may be the online tracking of internal rhythms while adjusting external pacemakers to endogenous brain activity, for example by potentially speeding up or slowing down ongoing frequencies and thereby modifying attentional and learning mechanisms in closed-loop paradigms.

4.5.4. Future applications in studying higher cognition

Frequency tagging has proven its great potential to assess the attention to and processing of sensory content directly on the neural level. Frequency tagging has so far been used to study visual foraging, including overt and covert attention processes, such as object and background processing. These paradigms are highly promising and will hopefully inspire further research into these and similar directions. For example, the frequency tagging method could be applied during joint attention to study the effect of social contexts on early attention processes in mobile EEG and dual-EEG paradigms. The high signal to noise ratio in those paradigms may be particularly fruitful for taking neuroscience into the interactive context and the real world.

A further potential lies in the study of covert attention. RVS studies can give us insights into the dynamics of infant visual attention that go beyond what can be inferred based on overt looking behavior using eye-tracking (Christodoulou et al., 2018; Robertson et al., 2012). This feature of the method opens interesting possibilities for research on early learning and could improve our understanding of the mechanisms guiding how and what infants attend to and preferentially process in their complex and dynamic environments.

An exciting further avenue for developmental research would be to combine RVS with rhythmic stimulation in other modalities, for example to study multimodal integration processes (Clouter et al., 2017) or the effects of cross-modal enhancement on learning processes (Albouy et al., 2022).

5. Conclusion

Past studies have proven that RVS can be applied in variable and powerful ways to gain unique insights into the human brain and its development. However, only recently developmental researchers started to use RVS to investigate phenomena beyond basic visual processing, paving the way forward to better understand social and cognitive development. Yet, the method is not without limitations, and future research is called for to improve our understanding of the RVS response. In our view, RVS is likely to become a leading noninvasive neuroimaging approach to study neurocognitive development in various lower and higher domains of infant cognition, and we hope that our review provides researchers with a useful context for its future applications.

Declaration of Competing Interest

There are no conflicts of interest.

Data availability

This is a review article, which includes a fully searchable database of the systematic review in the supplementary material (Appendix A).

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.dcn.2023.101315.

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