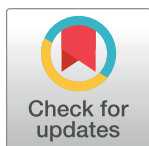


## RESEARCH ARTICLE

# Predicting the unpredicted . . . brain response: A systematic review of the feature-related visual mismatch negativity (vMMN) and the experimental parameters that affect it

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## Abstract

In this systematic review and meta-analysis, I consider aspects of experimental design that affect the visual mismatch negativity (vMMN)—an electrophysiological (neural) correlate of prediction error in vision that is typically largest between 150 ms and 300 ms in the event-related potential (ERP) at occipito-parietal regions on the scalp. I compiled data from 145 published studies investigating changes in a single property or feature of visual input. This review provides a concise summary of the vMMN literature on unexpected changes in features of visual input, outlining the most used (according to review) and optimal (following discussion on theoretical and practical implications) parameters of experiments investigating feature deviance for posterity as well as contemporary research. The data compiled was analysed to reveal meaningful relationships between aspects of experimental design and vMMN mean amplitude and peak latency. Results suggest that whether a control for adaptation is used, whether attention is towards vs. away from the stimulus of interest, and stimulus presentation time determines mean amplitude. Whether attention is towards vs. away from the stimulus of interest, the time between the stimulus of interest, deviant probability, and the number of standards separating deviants determines peak latency. There is also some indication that magnitude of deviance affects mean amplitude in studies exploring orientation deviance. This review and its findings elucidate potentially fruitful areas of future research.

## OPEN ACCESS

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## 1. Introduction

This review considers the evidence for aspects known (and perhaps unknown) for affecting the visual mismatch negativity (vMMN)—a canonical signature for prediction error in the visual system. To appreciate the factors that may affect the vMMN, this review considers how the vMMN is evoked and how it is measured.

Näätänen, Gaillard, and Mäntysalo [1] discovered an electrophysiological index of extra brain processing for unexpected changes in auditory input—the mismatch negativity (MMN). Näätänen [2] initially conceptualised the MMN as a mismatch signal, evoked by a physical mismatch between the memory trace of a repeated stimulus and a current stimulus—hence the *mismatch* in MMN. This conceptualization has evolved and the MMN is now widely regarded as a neural correlate of deviance detection/prediction error—an integral component in predictive coding theory [3–9].

The MMN is a ubiquitous phenomenon, occurring in sleeping infants [10, 11], comatose patients [12, 13], and in animals, such as cats [14] and mice [15]. The MMN occurs for many kinds of unanticipated change in auditory input, including auditory input that violates a category or rule established by the regularly occurring auditory input. For example, irregular tonal repetitions heard in sequences of rising or falling tones evoke the MMN [16]. Similarly, if a rule dictates one pairing of features (e.g., the higher the frequency, the louder the tone), a tone that does not adhere to the rule (e.g., a higher frequency paired with a quieter tone) will evoke the MMN [17]. These kinds of violations represent abstract irregularities and their capacity to evoke the MMN support the conceptualisation of the MMN as a prediction error rather than a mismatch signal.

The MMN provides valuable insights into how the brain processes and detects changes in auditory stimuli without conscious awareness, revealing unconscious processing, predictive coding, and how the brain adapts to its environment. The MMN is also altered in various neurological and psychiatric conditions, therefore, studying these alterations can provide valuable insights into the underlying neural mechanisms of these disorders and potentially serve as biomarkers to guide treatment [6, 7, 18]. Given the powerful utility of the MMN, researchers inevitably explored and discovered analogues of the MMN in other sensory modalities, including olfaction [19], touch [20], and vision [21]. This review is concerned with the vMMN.

Historically, two paradigms have dominated the field of vMMN/MMN research (for a discussion of evolving paradigms see [22]). The oddball paradigm is the traditional and still most popular paradigm [23]. In the oddball paradigm, there are regularly appearing standard stimuli that are interrupted by infrequent deviant stimuli that differ from the standard. In the roving variant of the oddball paradigm, the standards following the deviant are identical to the deviant and, therefore, the deviant of the prior sequence becomes the first standard of the next sequence.

The second paradigm is the multi-feature paradigm [24]. In the multi-feature paradigm, every second trial (i.e., the trial after every standard) is a deviant because a single property of visual input, as opposed to the whole stimulus, determines whether the stimulus represents a standard or a deviant, and while all other properties are unchanged, one deviant can represent a standard with respect to another property. This allows one to test different deviants within a short time, making it an attractive alternative to the oddball paradigm.

The common means of visualizing vMMN is by subtracting the event-related potential (ERP) for the standard from the ERP to the deviant, producing a deviant-minus-standard difference wave with a negativity between 150 ms and 300 ms after stimulus onset at parieto-occipital regions. This is known as the classic vMMN. However, amplitude differences revealed in this way also contain adaptation-related differences, because deviants are physically different from standards and standards occur more frequently than deviants. Adaptation effects refer to changes in neural responses based on recent sensory input and its relation to current stimuli. A key result of adaptation is repetition suppression, where neural responses decrease for repeated versus new stimuli (reviewed in [25]). The increased negativity owing to deviance detection/prediction error *and* adaptation are known as deviant-related negativity (DRN, (e.g., [26–28])). There are two popular methods for controlling for and separating adaptation-related

differences (for a review of the mechanisms which underscore adaptation-related differences see [29]. These are the equiprobable control [30] and the cascadic control [31]. While there has been recent discussion about whether the current control paradigms can effectively isolate the effects which make up the adaptation-related differences [32], these paradigms are currently the most popular methods for distinguishing adaptation-related differences from genuine deviance detection.

In an equiprobable control, all standards are replaced with equally probable random stimuli. The deviant is left unchanged and is renamed control. The cascadic control is similarly constructed; however, where there is no regularity in the equiprobable control, there is an uninterrupted regularity in the cascadic control. In both controls the deviant and control are (i) identical to each other, (ii) different from all other stimuli, and (iii) equally infrequent in their respective sequences. Therefore, the ERP for the control provides a measure of adaptation-related difference so that any remaining difference is because there is an irregularity in the oddball sequence but no such violation in the control sequence (i.e., prediction error). Any activity that remains is thought to reflect deviance detection/prediction error and is revealed by subtracting the ERP for the control from the ERP to the deviant, producing a deviant-minus-control difference wave, revealing the genuine vMMN free from adaptation-related differences. Paavilainen et al. distinguished the “genuine” MMN from the classic MMN contributed to by adaptation [33]. A similar distinction is made in the vMMN field [34].

The vMMN has been reported for a variety of visual irregularities, including, but not limited to, faces of different genders [35, 36], changes in facial expressions [37–46], food among non-food items [47], hand laterality [48, 49], asymmetrical patterns appearing among symmetrical patterns [50], object-based irregularities [51, 52], numeric irregularities (i.e., number of items expected to appear [53]), and even semantic irregularities based on word pairings [54]. These findings illustrate how readily the visual system encodes higher-order regularities.

Relatively simple deviants have also been used to evoke the vMMN. I refer to these as feature deviants because they differ from standards in some physical property or dimension (i.e., feature) of the visual stimulus. Some of the earliest publications of the vMMN were to changes in orientation (e.g., [55]), luminance (e.g., [56]), spatial frequency (e.g., [57]), colour (e.g., [58]), and shape or size (e.g., [26]). Interestingly, some recent studies have failed to find a vMMN for isolated changes in physical properties of visual stimuli, particularly those processed at the earliest stages of the visual system’s processing hierarchy, such as orientation and contrast [34, 59], encouraging one to consider what aspects of experimental design, including the feature itself, predicts vMMN characteristics or presence.

Accordingly, the current work’s objectives are to delineate which aspects of experimental design affect the vMMN or its presence. To that end, I reviewed the vMMN literature in which feature deviants were used to evoke the vMMN. This tabulated summary of the literature summarises the state of this research and allows for exploratory analyses of the aggregated vMMN data, potentially uncovering overarching trends that individual studies, limited by methodological differences or sample sizes, may fail to show.

## 2. Methods

### 2.1. Literature search and study selection

A systematic search was conducted on 3 April 2024. Published studies were identified in Scopus, Web of Science, and Google Scholar using the following Boolean search: (“mismatch negativity” OR vMMN) and (vision OR visual OR “visual feature” OR “deviant feature”) and (spatial frequency OR color OR colour OR orientation OR size OR shape OR phase OR

luminance OR location OR "motion direction" OR motion OR contrast OR duration OR omission) by author AM.

The following criteria were necessary for inclusion: (i) original peer-reviewed articles written in English (e.g., the data is original and not published elsewhere such as reviews, books, protocols, and conference abstracts), (ii) data from at least one healthy adult sample is reported, (iii) ERP data is reported and (iv) brain activity was isolated to visual processing in at least one condition.

Studies were excluded if (i) in all conditions the change in the visual stimulus was relatively complex such that higher-order processing would become necessary such as facial or emotional expressions, associative relationships, and lexical stimuli, or (ii) the vMMN or negativity for deviants in the vMMN time-window was not reported/shown. Studies in which authors described the increased negativity to deviants as something other than vMMN were not excluded. For example, Kenemans et al. [36] described the response as rareness-related negativity (see also [37]). Others have described it as change-related negativity (e.g., [38]), N200/N2 difference (e.g., [39–41]), or N270 [42].

After removing duplicates, abstracts were screened for inclusion criteria (original peer-reviewed articles written in English, visual ERP data from at least one healthy adult sample). The remaining publications were examined (whole text) for exclusion criteria (brain activity was not isolated to visual processing in at least one condition and/or the change in the visual stimulus was relatively complex such that higher-order processing would become necessary). Quality and bias assessment of included studies was conducted via the Review Manager (RevMan version 5.3) software for Cochrane reviews.

## 2.2. Data extraction and tabulation

For consistency, outcome measures were mean amplitude (not peak amplitude) and peak latency. These were estimated from figures where possible. I denote where peak latencies were calculated as the midpoint of the time-window of interest because (i) peak latencies were not reported, and (ii) there are no difference waves from which to derive an accurate peak latency estimate. Where authors report no significant negativity for an experiment or condition but there are no values or figures from which to obtain a value, a mean amplitude of "0" appears italicized in red and boldface. Otherwise, where there was a significant negativity but mean amplitude was not reported and could not be estimated from figures, I leave a blank. Where there is no significant vMMN, peak latency is blank.

I give details of separate conditions of a single experiment where multiple feature deviants were tested (one row for each feature). I give details of all conditions that did not produce a vMMN. Where multiple conditions of an experiment produced a vMMN, I give details of the condition that produced the largest negativity. When a significant deviant-minus-standard difference exists, yet there is no deviant-minus-control difference, I give details of both deviant-minus-standard and deviant-minus-control mean amplitudes (e.g., [60]). When both are significant, I give the deviant-minus-control mean amplitude only. Mean amplitudes appear in red where negativity was not significant (i.e., no vMMN reported for that condition).

In addition to mean amplitude and peak latency, the following were extracted for each entry. I leave a blank where a piece of information was absent.

- Authors.
- Publication year.
- Deviant feature.

- The number of participants in the corresponding data for a given condition or experiment (N).
- The stimulus of interest (SOI) and whether it appeared centrally or peripherally.
- SOI height (H) and width (W) in degrees of visual angle ( $^{\circ}$ VA).
- Background colour (BG).
- Whether the participant's task was visual, auditory, or manual.
- The stimulus that occupied the participant's attention.
- The difference between the standard and the deviant (D–S) in the units measured, for example, degrees ( $^{\circ}$ ), candles per meter squared ( $\text{cd}/\text{m}^2$ ), or cycles per degree (cpd).
- SOI duration and their inter-stimulus-interval (ISI) in milliseconds (ms) rounded to the nearest whole integer. If SOI duration or ISI was variable or jittered, the shortest SOI duration and longest ISI appears italicized in boldface.
- Deviant probability (D %) within the oddball sequence (as a proportion of 1) if stated.
- The minimum number of standards (Min. S) between deviants if stated.
- Whether the authors compared physically identical stimuli.
- Whether there was a control for adaptation.
- The reference for processing the EEG data.
- Method of ocular artifact rejection or correction.
- Low-pass (LP) and high-pass (HP) filters used to process the data (in Hz).
- Electrode or region of interest (ROI) from which mean and/or latency was reported.
- The vMMN time-window used to extract mean amplitudes (in ms).
- Mean amplitude of the genuine vMMN or classic vMMN where there was no control (to two decimal places in  $\mu\text{V}$ ).
- The time of vMMN peak latency (nearest whole integer in ms).

### 2.3. Meta-analytic procedure

Statistical analyses were performed in SPSS. One-way ANOVAs were used to explore the effect of *deviant feature*. I performed forward linear regression analyses on vMMN amplitude and peak latency separately. Including deviant feature a total of 10 predictors were:

1. SOI duration (in ms rounded to the nearest whole integer).
2. ISI duration (in ms rounded to the nearest whole integer).
3. Deviant probability (as a proportion of 1).
4. The minimum number of standards between deviants (0 is none stated).
5. Whether a minimum number of standards was specified or not.
6. Whether attention was towards vs. away from the SOI.
7. Whether there was a fixation task or not.

8. Whether there was a physical control or not.
9. Whether there was a control for adaptation or not.
10. Deviant feature.

Because magnitude of deviance standard vs. deviant differences for most properties of visual input were not easily standardized, the aforementioned analysis did not include magnitude of deviance as a predictor. Instead, magnitude of deviance effect was examined in orientation and spatial frequency entries separately, post-standardization. For orientation entries, magnitude of deviance for orientation was standardized as the difference between the deviant and the standard orientation, divided by 90 if  $\leq 90^\circ$  or minus 90 and then divided by 90 if  $> 90^\circ$  (e.g., if the deviant had an orientation of  $90^\circ$  and the standard had an orientation of  $180^\circ$ , the difference is 1 or if the deviant had an orientation of  $155^\circ$  and the standard had an orientation of  $45^\circ$ , the difference is 0.22). The calculation ensures orientation changes that are  $> 90^\circ$  are not represented as larger magnitudes of deviance than same orientation changes that are  $< 90^\circ$ .

For spatial frequency entries, magnitude of deviance for spatial frequency was standardized as the (absolute) difference between deviant and standard and divided by the larger spatial frequency (e.g., if the deviant had a spatial frequency of 1.2 cpd and the standard had a spatial frequency of 0.6 cpd, the difference is 0.5). Initially, analyses included predictors identified as influencing the vMMN amplitude or latency in their respective analysis. Thereafter, analyses included all 10 predictors (excluding deviant feature and including magnitude of deviance).

### 3. Results

#### 3.1. Included studies

After removing duplicates, 948 records were screened for inclusion criteria (original peer-reviewed articles written in English). The remaining 850 records were examined for further inclusion criteria. Of these, 250 had visual ERP data. Of these, 243 also had at least one healthy adult sample.

A further 98, were excluded because there was no vMMN data and/or the change in the visual stimulus was relatively complex such that higher-order processing would become necessary. Systematic review data and flow chart in supplementary materials (S1 Data).

Ultimately, 145 published peer-reviewed articles reported at least one condition in which they manipulated a relatively non-complex element of visual stimuli, such as orientation, contrast, luminance, spatial frequency, colour, shape/size, location, motion direction, duration/omission, or phase. The summary of risk of bias suggests a low proportion of vMMN studies indicate effect sizes (details in supplementary materials S2 and S3 Texts). To increase review sensitivity, studies were not excluded based on presence/absence of effect size or any of the captured variables including mean and peak amplitudes.

**Table 1** typifies the existing approach to vMMN research while also illustrating the kinds of feature deviants that have been used to evoke the vMMN. Entries are chronologically ordered by deviant feature.

Where there are multiple entries for the same deviant type, a condition or experiment is denoted in square brackets in the study identifier. There are 76 entries for orientation, 6 entries for contrast, 8 for luminance, 28 for spatial frequency, 39 for colour, 27 for shape/size, 12 for location, 15 for motion, 26 for duration/omission, and 1 entry for phase, for a total of 238 entries.

Mean amplitude was estimated for 107 entries. Peak latency was estimated for 110 entries. Overall, vMMNs with later peak latencies were larger than vMMNs with earlier peak latencies,  $r(158) = -0.242$ ,  $p = .002$  (two-tailed, listwise exclusion). The average mean amplitude for

Table 1. Systematic review of studies in which the deviant is a single feature of the visual stimulus.

| Study                            | N  | SOI                               | W<br>(°VA) | H<br>(°VA) | BG Colour | Task<br>Modality | Attention On            | D-S  | SOI<br>(ms) | ISI<br>(ms) | D%   | Min.<br>S | PC            | AC            | Ref              | Ocular-artifact<br>correction             | HP<br>(Hz) | LP<br>(Hz) | Epoch     | ROI                     | mean<br>vMMN<br>( $\mu$ V) | peak<br>vMMN<br>(ms) | Time-<br>window |
|----------------------------------|----|-----------------------------------|------------|------------|-----------|------------------|-------------------------|------|-------------|-------------|------|-----------|---------------|---------------|------------------|-------------------------------------------|------------|------------|-----------|-------------------------|----------------------------|----------------------|-----------------|
| <b>Orientation</b>               |    |                                   |            |            |           |                  |                         |      |             |             |      |           |               |               |                  |                                           |            |            |           |                         |                            |                      |                 |
| Czigler_1990 [61]                | 9  | Chevrans within rectangular frame | 1.27       | 0.77       |           | Visual           | Chevron deviants        | 180° | 83          | 417         | 0.20 | 2         | none          | none          | Linked-earlobes  | rejection: EOG threshold exclusion        | 0.20       | 50         | 0–768     | Oz                      | -3.76a                     | 237a                 | 210–270         |
| Fu_2003 [62]                     | 12 | Central square-wave gratings      | 3.20       | 3.20       | Black     | Visual           | Spatial Frequency       | 90°  | 100         | 100         | 0.10 | 1         | Reverse roles | none          | Right mastoid    | rejection; discard epochs with eye blinks | 0.10       | 40         | -200–800  | Occipital               | -1.90a                     | 192                  | 180–220         |
| Astikainen_2004 [63]             | 8  | Central light bar                 |            | 3.40       | Black     | Auditory         | Words                   | 90°  | 50          | 450         | 0.10 | 2         | Deviant alone | none          | Linked-mastoids  | rejection: EOG/EEG threshold exclusion    | 0.10       | 30         | -50–500   | Pz                      | -1.28a                     | 180b                 | 160–200         |
| Henderson_2006 [64]              | 12 | Peripheral Gabor patches          |            |            | Grey      | Visual           | Fixation square         | 90°  | 100         | 900         | 0.20 |           | Reverse Roles | none          | Right mastoid    | rejection: EOG threshold exclusion        | 0.08       | 100        | -100–800  | P10                     | -1.00a                     |                      | 180–320         |
| Astikainen_2008 [Short SOA] [65] | 10 | Central dark bar                  |            | 3.90       | Grey      | Auditory         | Words                   | 36°  | 100         | 400         | 0.10 | 2         | Reverse roles | Equi-probable | Average          | rejection: EOG/EEG threshold exclusion    | 0.10       | 30         | -100–500  | Occipital               | -0.69a                     | 195b                 | 185–205         |
| Astikainen_2008 [Long SOA] [65]  | 10 | Central dark bar                  |            | 3.90       | Grey      | Auditory         | Words                   | 36°  | 100         | 1,100       | 0.10 | 2         | Reverse roles | Equi-probable | Average          | rejection: EOG/EEG threshold exclusion    | 0.10       | 30         | -100–500  | Occipital               | 0.27a                      |                      | 185–205         |
| Kimura_2009 [66]                 | 12 | Central grey bar                  | 0.50       | 3.00       | Grey      | Visual           | Bar edges               | 36°  | 100         | 500         | 0.20 | 2         | Reverse roles | Equi-probable | Nose-tip         | rejection: EOG/EEG threshold exclusion    | 0.10       | 30         | -100–400  | T6(P8)                  | -1.60a                     | 225b                 | 200–250         |
| Czigler_2009 [67]                | 14 | Peripheral grid pattern           |            | 9.30       | Grey      | Visual           | Target quadrangle width | 90°  | 68          | 702         | 0.07 | 10        | none          | none          | Linked-mastoids  | rejection: EOG/EEG threshold exclusion    | 0.10       | 30         | -100–500  | Right posterior         | -1.01a                     | 280b                 | 270–290         |
| Czigler_2010 [68]                | 24 | Peripheral line segments          | 0.04       | 0.37       | Grey      | Visual           | Central line segment    | 30°  | 70          | 290         | 0.15 |           | Reverse roles | none          | Average mastoids | rejection: EOG/EEG threshold exclusion    | 0.15       | 30         | -100–500  | Oz                      | -0.60                      | 166                  | 162–170         |
| Sulykos_2011 [69]                | 12 | Peripheral Gabor patches          | 0.80       | 0.80       | Black     | Visual           | Spaceship               | 90°  | 80          | 480         | 0.18 |           | Reverse roles | none          | Linked-mastoids  | rejection: EOG/EEG threshold exclusion    | 0.10       | 30         | -100–400  | Oz                      | -2.55                      | 130                  | 121–131         |
| Tomio_2012 [Deviant 1] [70]      | 13 | Ramachandran visual pattern       | 4.60       | 3.90       | Grey      | Auditory         | Nursery stores          | 90°  | 100         | 1,000       |      |           | none          | none          | Linked-earlobes  | rejection: EOG/EEG threshold exclusion    | 0.50       | 60         | -16.8–700 | Pz                      | 0.00                       |                      |                 |
| Tomio_2012 [Deviant 2] [70]      | 13 | Ramachandran visual pattern       | 4.60       | 3.90       | Grey      | Auditory         | Nursery stores          | 180° | 100         | 1,000       |      |           | none          | none          | Linked-earlobes  | rejection: EOG/EEG threshold exclusion    | 0.50       | 60         | -16.8–700 | Pz                      |                            | 275                  |                 |
| Kimura_2013 [28]                 | 22 | Peripheral grey bars              | 0.40       | 3.00       | Grey      | Visual           | Fixation dot            | 33°  | 250         | 250         | 0.09 | 1         | Reverse roles | Equi-probable | Nose-tip         | rejection: EOG/EEG threshold exclusion    | 1.00       | 30         | -100–500  | PO8                     | -0.93a                     | 226b                 | 221–231         |
| Sulykos_2013 [71]                | 12 | Peripheral Gabor patches          | 1.00       | 1.00       | Dark      | Visual           | Spaceship               | 30°  | 80          | 610         | 0.07 | 12        | Equi-probable | Equi-probable | Average          | rejection: EOG/EEG threshold exclusion    | 1.00       |            | -100–400  | Parieto-occipital       | -0.05a                     |                      | 140–350         |
| Takács_2013 [Experiment 1] [72]  | 17 | Peripheral Gabor patches          | 1.60       | 1.60       | Grey      | Visual           | Fixation dot            | 50°  | 100         | 500         | 0.17 | 3         | Reverse roles | none          | Average          | rejection: EOG/EEG threshold exclusion    | 0.10       | 30         | -100–400  | Parieto-occipital       | -0.65                      | 134                  | 120–140         |
| Takács_2013 [Experiment 2] [72]  | 19 | Peripheral Gabor patches          | 1.60       | 1.60       | Grey      | Visual           | Fixation dot            | 90°  | 100         | 500         | 0.17 | 3         | Reverse roles | none          | Average          | rejection: EOG/EEG threshold exclusion    | 0.10       | 30         | -100–400  | Parieto-occipital       | -0.84                      | 148                  | 116–176         |
| Shi_2013 [73]                    | 12 | Peripheral red rectangles         | 0.10       | 0.30       | White     | Visual           | Fixation cross          | 90°  | 50          | 550         | 0.10 | 1         | none          | none          | Nose-tip         | correction; corrected via EOG regression  | 0.10       | 100        | -100–400  | Occipito-temporal       | -1.60                      | 200b                 | 150–250         |
| Wu_2013 [74]                     | 12 | Peripheral rectangles             | 3.44       | 1.15       |           | Visual           | Central number task     | 90°  | 50          | 550         | 0.10 | 1         | none          | none          | Nose-tip         | correction: EOG artifact correction       | 0.10       | 100        | -100–400  |                         |                            | 192                  | 150–200         |
| Kimura_2014 [Experiment 1] [75]  | 23 | Central grey bar                  | 1.00       | 6.00       | Black     | Manual           | Visuo-motor task        | 22°  | 250         | 603         | 0.18 |           | Reverse roles | none          | Nose-tip         | rejection: EOG/EEG threshold exclusion    | 1.50       | 30         | -100–500  | Right occipito-temporal | -1.19                      | 225b                 | 200–250         |
| Kimura_2014 [Experiment 2] [75]  | 21 | Central grey bar                  | 1.00       | 6.00       | Black     | Manual           | Visuo-motor task        | 22°  | 250         | 610         | 0.18 |           | Reverse roles | none          | Nose-tip         | rejection: EOG/EEG threshold exclusion    | 1.50       | 30         | -100–500  | Right occipito-temporal | -0.92                      | 265b                 | 240–290         |
| Noyez_2014 [76]                  | 20 | Peripheral Chevrons               | 1.40       | 1.40       | Grey      | Visual           | Central Chevrans        | 180° | 50          | 1,000       | 0.10 |           | none          | none          | Average          | rejection: visual inspection              | 0.25       | 60         | -236–464  | Posterior               | -0.36a                     | 214b                 | 144–284         |
| Wang_2014a [77]                  | 14 | Peripheral facial models          | 3.68       | 3.42       | White     | Visual           | Fixation cross          | 90°  | 100         | 500         | 0.13 | 2         | Equi-probable | Equi-probable | Nose-tip         | correction; corrected via EOG regression  | 0.05       | 30         | -100–600  | P9/10                   | -1.90                      | 225b                 | 150–300         |

(Continued)

Table 1. (Continued)

| Study                                      | N  | SOI                                      | W<br>(°VA) | H<br>(°VA) | BG Colour                | Task<br>Modality | Attention On        | D-S | SOI<br>(ms) | ISI<br>(ms) | D%<br>S | PC                              | AC            | Ref             | Ocular-artifact<br>correction                       | HP<br>(Hz) | LP<br>(Hz) | Epoch    | ROI                        | mean<br>vMMN<br>(µV) | peak<br>vMMN<br>(ms) | Time-<br>window |
|--------------------------------------------|----|------------------------------------------|------------|------------|--------------------------|------------------|---------------------|-----|-------------|-------------|---------|---------------------------------|---------------|-----------------|-----------------------------------------------------|------------|------------|----------|----------------------------|----------------------|----------------------|-----------------|
| Wang_2014b [78]                            | 16 | Peripheral faces                         | 3.42       | 3.68       | Grey                     | Visual           | Fixation cross      | 90° | 100         | 500         | 0.20    | Reverse Roles                   | none          | Nose-tip        | correction; corrected via EOG regression            | 0.05       | 30         | -100–500 | Occipito-temporal          | -2.50                | 175a                 | 140–200         |
| Qian_2014 [79]                             | 14 | Peripheral red rectangles                | 0.10       | 0.30       | White                    | Visual           | Fixation cross      | 90° | 50          | 550         | 0.10    | none                            | none          | Nose-tip        | rejection; EOG/EEG threshold exclusion              | 0.10       | 100        | -100–500 | Occipital-temporal         | 1.07                 | 200a                 | 150–250         |
| Furkaas_2015 [80]                          | 27 | Peripheral Gabor patches                 | 7.70       | 7.70       | Grey                     | Visual           | Fixation cross      | 90° | 200         | 480         | 0.20    | Reverse roles                   | none          | Average         | correction; ICA                                     | 0.10       | 30         | -100–600 | Sagittal parieto-occipital | -0.30                | 145b                 | 90–200          |
| Jack_2015 [81]                             | 12 | Annular sine-wave grating                | 3.20       | 3.20       | Grey                     | Visual           | Grating orientation | 45° | 500         | 16          | 0.20    | Equi-probable                   | Equi-probable | Linked-earlobes | rejection; EOG/EEG threshold exclusion              | 0.10       | 35         | -100–500 | Right Posterior            | -1.71a               | 250                  | 240–290         |
| Kimura_2015 [82]                           | 22 | Peripheral grey bars                     | 0.40       | 3.00       | Black                    | Visual           | Fixation dot        | 33° | 250         | 250         | 0.09    | Reverse roles                   | Equi-probable | Nose-tip        | rejection; EOG/EEG threshold exclusion              | 0.10       | 30         | -100–500 | PO8                        | -1.16                | 202b                 | 197–207         |
| Sulykos_2015 [83]                          | 14 | LoVF matrix of "N"                       | 16.10      | 3.90       | Black                    | Visual           | Spaceship           | 90° | 300         | 617         | 0.17    | Reverse roles                   | none          | Nose-tip        | rejection; EOG/EEG threshold exclusion              | 0.10       | 30         | -100–500 | Parieto-occipital          | -1.03                | 140                  | 130–150         |
| Sulykos_2015 [83]                          | 14 | LoVF matrix of oblique bars              | 16.10      | 3.90       | Black                    | Visual           | Spaceship           | 90° | 300         | 617         | 0.17    | Reverse roles                   | none          | Nose-tip        | rejection; EOG/EEG threshold exclusion              | 0.10       | 30         | -100–500 | Parieto-occipital          | -1.23                | 127                  | 117–137         |
| Meng_2015 [Supra-threshold condition] [84] | 15 | Central Tumbling E otypes                |            |            | Black                    | Auditory         | /nə/ sound          | 90° | 300         | 500         | 0.13    | Equi-probable                   | Equi-probable | Nose-tip        | correction; EOG/artifact correction                 | 0.10       | 100        | -200–800 | Occipito-temporal          | -2.58                | 332                  | 270–430         |
| Meng_2015 [Sub-threshold condition] [84]   | 15 | Central Tumbling E otypes                |            |            | Black                    | Auditory         | /nə/ sound          | 90° | 300         | 500         | 0.13    | Equi-probable                   | Equi-probable | Nose-tip        | correction; EOG/artifact correction                 | 0.10       | 100        | -200–800 | Occipito-temporal          | -0.06                |                      | 270–430         |
| Li_2017 [85]                               | 12 | Peripheral polygons                      | 0.57       | 1.70       | Grey                     | Manual           | Visuo-motor task    | 90° | 50          | 600         | 0.17    | Equi-probable                   | Equi-probable |                 | correction; removed influence of EOG on other leads |            |            | -100–400 | Right occipito-temporal    | -0.66a               | 195a                 | 175–225         |
| Durant_2017 [Deviant 1 D-C] [60]           | 15 | Peripheral Gabor patches                 | 2.45       | 2.45       | Grey                     | Visual           | Fixation dot        | 74° | 120         | 600         | 0.17    | Equi-probable                   | Equi-probable | Nose-tip        | rejection; EOG/EEG threshold exclusion              | 0.10       | 30         | -100–400 | Right parieto-occipital    | 0.00                 |                      | 150–250         |
| Durant_2017 [Deviant 1 D-S] [60]           | 15 | Peripheral Gabor patches                 | 2.45       | 2.45       | Grey                     | Visual           | Fixation dot        | 74° | 120         | 600         | 0.17    | none                            | none          | Nose-tip        | rejection; EOG/EEG threshold exclusion              | 0.10       | 30         | -100–400 | OZ                         | 0.24a                |                      | 150–250         |
| Durant_2017 [Deviant 2 D-C] [60]           | 15 | Peripheral Gabor patches                 | 2.45       | 2.45       | Grey                     | Visual           | Fixation dot        | 86° | 120         | 600         | 0.17    | Equi-probable                   | Equi-probable | Nose-tip        | rejection; EOG/EEG threshold exclusion              | 0.10       | 30         | -100–400 | Right parieto-occipital    | 0.00                 |                      | 150–250         |
| Durant_2017 [Deviant 2 D-S] [60]           | 15 | Peripheral Gabor patches                 | 2.45       | 2.45       | Grey                     | Visual           | Fixation dot        | 86° | 120         | 600         | 0.17    | none                            | none          | Nose-tip        | rejection; EOG/EEG threshold exclusion              | 0.10       | 30         | -100–400 | Right parieto-occipital    | -0.61                | 196a                 | 150–250         |
| File_2017 [Experiment 1—cascade] [86]      | 15 | Peripheral line texture                  | 0.09       | 1.26       | Black                    | Visual           | Spaceship           | 36° | 100         | 500         | 0.12    | Reverse roles                   | Cascade       | Nose-tip        | rejection; EOG/EEG threshold exclusion              | 0.10       | 30         | -100–400 | Parieto-occipital          | -0.09                |                      | 105–190         |
| File_2017 [Experiment 1—equiprobable] [86] | 15 | Peripheral line texture                  | 0.09       | 1.26       | Black                    | Visual           | Spaceship           | 36° | 100         | 500         | 0.12    | Reverse roles                   | Equi-probable | Nose-tip        | rejection; EOG/EEG threshold exclusion              | 0.10       | 30         | -100–400 | Parieto-occipital          | 0.03                 |                      | 105–190         |
| Bodnar_2017 [87]                           | 17 | Peripheral line texture                  | 0.09       | 1.26       | Black                    | Visual           | Spaceship           | 90° | 100         | 400         | 0.12    | Reverse roles and Standard only | none          | Nose-tip        | rejection; EOG/EEG threshold exclusion              | 0.10       | 30         | -100–400 | Parieto-occipital          | -1.44                | 124b                 | 112–132         |
| Yan_2017 [88]                              | 15 | Peripheral black arrows                  | 3.42       | 3.68       | White                    | Visual           | Fixation cross      | 90° | 100         | 500         | 0.20    | 2                               | none          | Nose-tip        | correction; ICA                                     | 0.10       | 30         | -300–600 | Parieto-occipital          | -2.60a               | 200b                 | 100–300         |
| Urakawa_2017 [89]                          | 10 | Peripheral line segments                 | 0.10       | 1.90       | Black                    | Visual           | Central Necker cube | 90° | 250         | 250         |         | none                            | none          | Linked-earlobes | rejection; EOG/EEG threshold exclusion              | 0.50       | 50         | -200–600 | Or                         | -1.68a               | 300                  | 280–406         |
| Flynn_2017 [Deviant 1] [90]                | 9  | Central black-white checkerboard         | 31.60      | 28.60      | Complex coloured stimuli |                  | Fixation dot        | 45° | 14          | 500         | 0.20    | Deviant block                   | none          | Right mastoid   | rejection; online artifact rejection of eye blinks  | 1.00       | 30         | -100–500 | Occipital                  | -0.95                |                      | 155–195         |
| Flynn_2017 [Deviant 2] [90]                | 9  | Central black-white checkerboard         | 31.60      | 28.60      | Complex coloured stimuli |                  | Fixation dot        | 45° | 7           | 500         | 0.20    | Deviant block                   | none          | Right mastoid   | rejection; online artifact rejection of eye blinks  | 1.00       | 30         | -100–500 | Occipital                  | -0.06                |                      | 155–195         |
| Sulykos_2017 [Deviant 1] [91]              | 30 | Peripheral diamonds with their diagonals | 1.65       | 1.65       | Grey                     | Visual           | Central disc        | 90° | 480         | 560         | 0.20    | Reverse roles                   | none          | Nose-tip        | rejection; EOG/EEG threshold exclusion              | 0.10       | 30         | -100–400 | Occipital                  | -1.14                | 160a                 | 120–219         |

(Continued)

Table 1. (Continued)

| Study                                                              | N  | SOI                                      | W ('VA) | H ('VA) | BG Colour | Task Modality | Attention On                      | D-S  | SOI (ms) | ISI (ms) | D%   | Min. S | PC            | AC            | Ref      | Ocular-artifact correction                             | HP (Hz) | Epoch   | ROI                     | mean vMMN (μV) | peak vMMN (ms) | Time-window |
|--------------------------------------------------------------------|----|------------------------------------------|---------|---------|-----------|---------------|-----------------------------------|------|----------|----------|------|--------|---------------|---------------|----------|--------------------------------------------------------|---------|---------|-------------------------|----------------|----------------|-------------|
| Subkys_2017 [Deviant 2] [91]                                       | 30 | Peripheral diamonds with their diagonals | 1.65    | 1.65    | Grey      | Visual        | Central disc                      | 90°  | 460      | 560      | 0.20 |        | Reverse roles | none          | Nose-tip | rejection: EOG/EEG threshold exclusion                 | 0.10    | 100–400 | Occipital               | 0.00           |                | 120–219     |
| Zhang_2018 [92]                                                    | 24 | Central black arrow                      | 3.68    | 3.42    | White     | Visual        | Fixation cross                    | 90°  | 100      | 500      | 0.20 | 2      | none          | none          | Nose-tip | correction: corrected via EOG regression               | 0.05    | 100–600 | Parieto-occipital       | -2.44a         | 179            | 100–300     |
| Kimura_2018 [93]                                                   | 14 | Central grey bar                         | 0.90    | 5.70    | Black     | Visual        | Central grey bar                  | 45°  | 250      | 600      | 0.19 | 3      | none          | none          | Nose-tip | correction: ICA                                        | 1.00    | 100–700 | P8                      | -2.30          | 225b           | 200–250     |
| Urakawa_2018 [94]                                                  | 18 | Peripheral line segments                 | 1.90    | 0.10    | Black     | Visual        | Fixation cross                    | 90°  | 250      | 250      |      |        | Equi-probable | Equi-probable | Average  | none                                                   | 0.50    | 100–500 | Oz                      | -0.19a         | 188            | 134–252     |
| Kimura_2019 [95]                                                   | 35 | Central grey bar                         | 1.00    | 6.00    | Black     | Manual        | Visuo-motor task                  | 90°  | 250      | 50       | 0.20 |        | none          | none          | Nose-tip | correction: ICA                                        | 1.00    | 100–500 | Right occipito-temporal | -1.03          | 283a           | 270–350     |
| Smout_2019 [No attention condition] [96]                           | 24 | Central Gabor patches                    | 11.00   | 11.00   | Grey      | Visual        | Fixation dot                      | 20°  | 100      | 500      | 0.14 | 4      | Equi-probable | Equi-probable | Average  | correction: ICA                                        | 0.25    | 100–500 | PO8                     | 0.17a          |                | 150–350     |
| Smout_2019 [Attention condition] [96]                              | 24 | Central Gabor patches                    | 11.00   | 11.00   | Grey      | Visual        | Gabor patch spatial frequency     | 20°  | 100      | 500      | 0.14 | 4      | Equi-probable | Equi-probable | Average  | correction: ICA                                        | 0.25    | 100–500 | PO8                     | -0.63a         | 206a           | 150–350     |
| File_2019 [Attend far condition] [97]                              | 15 | LoVF Peripheral hourglass shapes         | 2.31    | 2.31    | Grey      | Visual        | Bars rotating task with bar above | 90°  | 500      | 500      | 0.20 |        | Reverse Roles | Equi-probable | Average  | rejection: EOG/EEG threshold exclusion + Eye-tracking' | 0.10    | 100–500 | PO4                     | -0.33a         |                | 140–210     |
| File_2019 [Attend close condition] [97]                            | 15 | LoVF Peripheral hourglass shapes         | 2.31    | 2.31    | Grey      | Visual        | Bars rotating task with bar below | 90°  | 500      | 500      | 0.20 |        | Reverse Roles | Equi-probable | Average  | rejection: EOG/EEG threshold exclusion + Eye-tracking' | 0.10    | 100–500 | PO4                     | -1.76          | 187a           | 140–210     |
| Pesonen_2019 [98]                                                  | 16 | Central dark bar                         |         | 3.90    | Grey      | Auditory      | Words                             | 36°  | 100      | 1,100    | 0.10 | 2      | none          | none          | Cz       | rejection: only noise-free trials averaged             | 0.10    | 100–400 | Occipital               | -1.02a         | 210            | 207–248     |
| Czigler_2019 [Deviant 1 offset] [99]                               | 18 | Peripheral diamonds with their diagonals | 0.33    | 9.90    | Grey      | Visual        | Central disc                      | 90°  | 460      | 560      | 0.20 | 1      | Reverse Roles | none          | Nose-tip | rejection: EOG/EEG threshold exclusion                 | 0.10    | 100–500 | Occipital               | -1.02          | 160            | 120–202     |
| Czigler_2019 [Deviant 2 offset] [99]                               | 18 | Peripheral white lines                   | 0.33    | 9.90    | Grey      | Visual        | Central disc                      | 90°  | 460      | 560      | 0.20 | 1      | Reverse Roles | none          | Nose-tip | rejection: EOG/EEG threshold exclusion                 | 0.10    | 100–500 | Occipital               | -0.76          | 162            | 120–202     |
| Czigler_2019 [Deviant 1 onset] [99]                                | 18 | Peripheral diamonds with their diagonals | 0.33    | 9.90    | Grey      | Visual        | Central disc                      | 90°  | 460      | 560      | 0.20 | 1      | Reverse Roles | none          | Nose-tip | rejection: EOG/EEG threshold exclusion                 | 0.10    | 100–500 | Occipital               | 0.17           |                | 120–202     |
| File_2020 [100]                                                    | 13 | LoVF Peripheral Diamonds                 | 0.14    | 4.21    | Grey      | Visual        | Bars rotating task and bar above  | 90°  | 500      | 500      | 0.20 |        | Reverse Roles | none          | Average  | rejection: EOG/EEG threshold exclusion + Eye-tracking' | 0.10    | 100–500 | PO4                     | -1.92          | 181            | 152–200     |
| Male_2020 [Experiment 1: Gabor-fixation condition] [34]            | 24 | Central Gabor patches                    | 3.00    | 3.00    | Grey      | Visual        | Fixation dot                      | 36°  | 100      | 400      | 0.20 | 2      | Equi-probable | Equi-probable | Nose-tip | correction: ICA + Eye-tracking                         | 0.10    | 100–400 | P8                      | 0.18           |                | 200–250     |
| Male_2020 [Experiment 2] [34]                                      | 24 | Central Gabor patches                    | 3.00    | 3.00    | Grey      | Visual        | Fixation dot                      | 36°  | 100      | 400      | 0.13 | 2      | Casacadic     | Casacadic     | Nose-tip | correction: ICA + Eye-tracking                         | 0.10    | 100–400 | P8                      | 0.25           |                | 200–250     |
| Male_2020 [Experiment 1: bar-fixation condition] [34]              | 24 | Central grey bar                         | 0.50    | 3.00    | Black     | Visual        | Fixation dot                      | 36°  | 100      | 400      | 0.20 | 2      | Equi-probable | Equi-probable | Nose-tip | correction: ICA + Eye-tracking                         | 0.10    | 100–400 | P8                      | 0.02           |                | 200–250     |
| Male_2020 [Experiment 1: bar-edge condition] [34]                  | 24 | Central grey bar                         | 0.50    | 3.00    | Black     | Visual        | Bar edges                         | 36°  | 100      | 400      | 0.20 | 2      | Equi-probable | Equi-probable | Nose-tip | correction: ICA + Eye-tracking                         | 0.10    | 100–400 | P8                      | 0.79           |                | 200–250     |
| Male_2020 [Experiment 1: Gabor-edge condition] [34]                | 24 | Central Gabor patches                    | 3.00    | 3.00    | Grey      | Visual        | Gabor patch edges                 | 36°  | 100      | 400      | 0.20 | 1      | Equi-probable | Equi-probable | Nose-tip | correction: ICA + Eye-tracking                         | 0.10    | 100–400 | P8                      | -0.13          |                | 200–250     |
| Petro_2020 [Experiment 1: task direction = orientation diff] [101] | 24 | Peripheral line segments                 | 0.77    | 0.11    | Grey      | Manual        | Visuo-motor task                  | 144° | 100      | 491      | 0.13 |        | Equi-probable | Equi-probable | Nose-tip | rejection: EOG/EEG threshold exclusion                 | 0.10    | 100–450 | Occipital               | 0.05           |                | 200–350     |
| Petro_2020 [Experiment 1: task direction = orientation diff] [101] | 24 | Peripheral line segments                 | 0.77    | 0.11    | Grey      | Manual        | Visuo-motor task                  | 144° | 100      | 491      | 0.13 |        | Equi-probable | Equi-probable | Nose-tip | rejection: EOG/EEG threshold exclusion                 | 0.10    | 100–450 | Occipital               | 0.15           |                | 200–350     |
| Petro_2020 [Experiment 2: task direction = orientation diff] [101] | 26 | Peripheral line segments                 | 0.77    | 0.11    | Grey      | Manual        | Visuo-motor task                  | 144° | 100      | 491      | 0.13 |        | Equi-probable | Equi-probable | Nose-tip | rejection: EOG/EEG threshold exclusion                 | 0.10    | 100–450 | Occipital               | 0.01           |                | 200–350     |

(Continued)

Table 1. (Continued)

| Study                                                              | N  | SOI                                  | W<br>(°VA) | H<br>(°VA) | BG Colour   | Task<br>Modality | Attention On             | D-S                | SOI<br>(ms) | ISI<br>(ms) | D%<br>S | PC            | AC            | Ref             | Ocular-artifact<br>correction                        | HP<br>(Hz) | LP<br>(Hz) | Epoch   | ROI                      | mean<br>vMMN<br>(µV) | peak<br>vMMN<br>(ms) | Time-<br>window |
|--------------------------------------------------------------------|----|--------------------------------------|------------|------------|-------------|------------------|--------------------------|--------------------|-------------|-------------|---------|---------------|---------------|-----------------|------------------------------------------------------|------------|------------|---------|--------------------------|----------------------|----------------------|-----------------|
| Petro_2020 [Experiment 2: task direction - orientation diff] [101] | 26 | Peripheral line segments             | 0.77       | 0.11       | Grey        | Manual           | Visuo-motor task         | 144°               | 100         | 491         | 0.13    | Equi-probable | Equi-probable | Nose-tip        | rejection: EOG/EEG threshold exclusion               | 0.10       | 30         | 100-450 | Occipital                | -0.14                |                      | 200-350         |
| Kurita_2021 [102]                                                  | 16 | Central blue/red grating             | 4.30       | 4.30       | Black       | Visual           | Grating color            | 90°                | 200         | 100         |         | none          | none          | Linked-earlobes | rejection: EOG/EEG threshold exclusion               | 0.50       | 300        | 100-500 | Oz                       | -1.86a               | 237                  | 100-250         |
| Tse_2021 [103]                                                     | 22 | Peripheral grey bars                 | 0.40       | 3.00       | Black       | Visual           | Fixation cross           | 33°                | 250         | 368         | 0.09    | Equi-probable | Equi-probable | Nose-tip        | correction: corrected via EOG regression             | 0.10       | 30         | 100-500 | O2                       | -0.45a               | 226a                 | 150-250         |
| Schlomacher_2022 [104]                                             | 25 | Peripheral white lines in matrix     | 10.00      | 10.00      | Black       | Visual           | Shape change             | 90°                | 100         | 700         | 0.20    | 1             | none          | Average         | rejection: visual inspection                         | 0.10       | 25         | 200-600 | Posterior                | -0.45a               | 262                  | 150-350         |
| Csikos_2023 [105]                                                  | 21 | LoVF Diamonds with their diagonals   | 1.57       | 1.57       | Grey        | Visual           | Fixation cross           | 90°                | 400         | 400         | 0.15    | Reverse roles | none          | Nose-tip        | correction: ICA                                      | 0.10       | 30         | 100-400 | Right parieto-occipital  | -1.05                | 135b                 | 120-150         |
| Male_2023 [Deviant 1] [106]                                        | 21 | Central Gabor patches                | 22.00      | 22.00      | Grey        | Visual           | Letters                  | 15°                | 80          | 280         | 0.18    | 2             | Equi-probable | Average         | correction: ICA                                      | 0.10       | 40         | 50-350  | Middle parieto-occipital | 0.16                 |                      | 197-207         |
| Male_2023 [Deviant 2] [106]                                        | 21 | Central Gabor patches                | 22.00      | 22.00      | Grey        | Visual           | Letters                  | 30°                | 80          | 280         | 0.18    | 2             | Equi-probable | Average         | correction: ICA                                      | 0.10       | 40         | 50-350  | Middle parieto-occipital | 0.25                 |                      | 197-207         |
| Male_2023 [Deviant 3] [106]                                        | 21 | Central Gabor patches                | 22.00      | 22.00      | Grey        | Visual           | Letters                  | 60°                | 80          | 280         | 0.18    | 2             | Equi-probable | Average         | correction: ICA                                      | 0.10       | 40         | 50-350  | Middle parieto-occipital | 0.22                 |                      | 197-207         |
| Male_2024 [CVF condition] [59]                                     | 18 | Central Gabor patches                | 4.00       | 4.00       | Grey        | Visual           | Fixation cross           | 33°                | 100         | 400         | 0.17    | 3             | Reverse roles | Average         | correction: ICA                                      | 0.01       | 40         | 100-400 | Right parieto-occipital  | -0.18a               |                      | 197-207         |
| Male_2024 [LoVF condition] [59]                                    | 16 | LoVF Gabor patches                   | 4.00       | 4.00       | Grey        | Visual           | Fixation cross           | 33°                | 100         | 400         | 0.17    | 3             | Reverse roles | Average         | correction: ICA                                      | 0.01       | 40         | 100-400 | Right parieto-occipital  | 0.00                 |                      | 197-207         |
| Contrast                                                           |    |                                      |            |            |             |                  |                          |                    |             |             |         |               |               |                 |                                                      |            |            |         |                          |                      |                      |                 |
| Nyman_1990 [107]                                                   | 9  | Peripheral square-wave gratings      | 2.00       | 2.00       |             | Visual           | Fixation dot             | -0.48 M            | 100         | 490         | 0.10    | Reverse roles | none          | Right mastoid   | rejection: EOG/EEG threshold exclusion               | 0.10       | 100        | 0-300   | Oz                       | -0.28                |                      | 100-200         |
| Luo_1997 [108]                                                     | 12 | Coloured scenery                     | 4.30       | 2.80       | Grey        | Visual           | Contrast increment       | Contrast increment | 28          | 672         | 0.18    | none          | none          | Nose-tip        | none                                                 | 0.10       | 40         | 50-550  | Oz                       | -1.75                | 168                  | 90-220          |
| Wei_2002 [109]                                                     | 12 | Coloured scenery                     | 2.46       | 1.60       | Stimulus    | Visual           | Contrast increment       | Contrast increment | 700         |             | 0.15    | none          | none          | Nose-tip        | correction: EOG automatically corrected by NeuroScan | 0.10       | 40         | 52-600  | Oz                       | -1.65a               | 152a                 | 150-200         |
| Male_2020 [Experiment 2] [34]                                      | 24 | Central Gabor patches                | 3.00       | 3.00       | Grey        | Visual           | Fixation dot             | +0.33 M            | 100         | 400         | 0.13    | 1             | Cascadic      | Nose-tip        | correction: ICA + Eye-tracking                       | 0.10       | 40         | 100-400 | P8                       | 1.00                 |                      | 200-250         |
| Male_2024 [CVF condition] [59]                                     | 18 | Central Gabor patches                | 4.00       | 4.00       | Grey        | Visual           | Fixation cross           | -0.453 M           | 100         | 400         | 0.17    | 3             | Equi-probable | Average         | correction: ICA                                      | 0.01       | 40         | 100-400 | Right parieto-occipital  | 0.07a                |                      | 150-200         |
| Male_2024 [LoVF condition] [59]                                    | 16 | LoVF Gabor patches                   | 4.00       | 4.00       | Grey        | Visual           | Fixation cross           | -0.453 M           | 100         | 400         | 0.17    | 3             | Equi-probable | Average         | correction: ICA                                      | 0.01       | 40         | 100-400 | Right parieto-occipital  | 0.00                 |                      | 150-200         |
| Luminance                                                          |    |                                      |            |            |             |                  |                          |                    |             |             |         |               |               |                 |                                                      |            |            |         |                          |                      |                      |                 |
| Stagg_2004 [56]                                                    | 12 | Peripheral white vertical bars       | 0.34       | 2.23       | Black       | Visual           | Fixation square          | 2.76 cd/m2         | 200         | 642         | 0.06    | Reverse roles | none          | Fz              | rejection: EOG/EEG threshold exclusion               | 0.05       | 100        | 0-512   | Occipital                | -1.67a               | 305b                 | 210-400         |
| Kimura_2010a [110]                                                 | 12 | Peripheral discs                     | 1.40       | 1.40       | Black       | Visual           | Fixation letter          | 127.36 cd/m2       | 150         | 450         | 0.20    | 4             | Reverse roles | Nose-tip        | rejection: EOG/EEG threshold exclusion               |            | 35         | 100-700 | PO7                      | -5.25                | 240b                 | 220-260         |
| Kimura_2010b [111]                                                 | 12 | Peripheral discs                     | 2.50       | 2.50       | Black       | Visual           | Fixation cross           | 76 cd/m2           | 80          | 720         | 0.20    | 1             | Reverse roles | Nose-tip        | rejection: EOG/EEG threshold exclusion               | 1.00       | 35         | 100-400 | Oz                       | -5.29                | 175b                 | 150-200         |
| Sulykos_2014 [112]                                                 | 14 | 3-ring concentric annuli             | 2.29       | 2.29       | Blue-violet | Visual           | Fixation cross           | 6.3 cd/m2          | 400         | 348         | 0.20    | 2             | Reverse roles | Average         | rejection: EOG/EEG threshold exclusion               | 0.10       |            | 100-400 | Posterior                | -0.64                | 201                  | 180-220         |
| Jack_2017 [113]                                                    | 10 | Annular sine-wave grating            | 3.20       | 3.20       | Black       | Visual           | Report binocular rivalry | 14.51 cd/m2        | 100         | 100         | 0.06    | 10            | Reverse roles | Average         | rejection: EOG/EEG threshold exclusion               | 0.10       | 40         | 100-400 | Right posterior          | -1.60a               | 250                  | 230-274         |
| Sulykos_2018 [114]                                                 | 15 | LoVF Peripheral Checkerboard pattern | 2.00       | 6.00       | Grey        | Visual           | Fixation dot             | 81.3 cd/m2         | 480         | 560         | 0.20    | 2             | Reverse roles | Nose-tip        | rejection: EOG/EEG threshold exclusion               | 0.10       | 30         | 100-500 | O2                       | -3.26                | 167                  | 154-174         |

(Continued)

Table 1. (Continued)

| Study                             | N  | SOI                                      | W (°VA) | H (°VA) | BG Colour | Task Modality       | Attention On              | D-S        | SOI (ms) | ISI (ms) | D% S | PC             | AC            | Ref                    | Ocular-artifact correction                                | HP (Hz) | LP (Hz) | Epoch   | ROI               | mean vMMN (µV) | peak vMMN (ms) | Time-window |
|-----------------------------------|----|------------------------------------------|---------|---------|-----------|---------------------|---------------------------|------------|----------|----------|------|----------------|---------------|------------------------|-----------------------------------------------------------|---------|---------|---------|-------------------|----------------|----------------|-------------|
| Petro_2021 [115]                  | 20 | Peripheral Checkerboard patterns         | 2.00    | 6.00    | Grey      | Visual              | Fixation dot              | 81.3       | 480      | 580      | 0.20 | Reverse roles  | none          | Nose-tip               | rejection: EOG/EEG threshold exclusion                    | 0.10    | 30      | 100–500 | Occipital         | -2.28a         | 129a           | 100–150     |
| Nie_2021 [116]                    | 30 | Peripheral Wifi symbols                  | 3.68    | 3.42    | White     | Visual              | Fixation cross            | grey-black | 100      | 500      | 0.20 | Reverse roles  | none          | Nose-tip               | rejection: EOG/EEG threshold exclusion                    |         | 30      | 100–500 | Occipital         | -0.65          | 195a           | 170–220     |
| Spatial Frequency                 |    |                                          |         |         |           |                     |                           |            |          |          |      |                |               |                        |                                                           |         |         |         |                   |                |                |             |
| Tales_1999 [Experiment 1] [117]   | 12 | Peripheral white vertical bars           | 0.68    | 2.20    | Black     | Visual              | Fixation square           | +0.6 cpd   | 200      | 642      | 0.06 | 2              | none          | Fz                     | rejection: EOG/EEG threshold exclusion                    |         | 70      | 0–512   | O2                | -4.00a         | 325b           | 250–400     |
| Tales_1999 [Experiment 2] [117]   | 12 | Peripheral white vertical bars           | 0.68    | 2.20    | Black     | Visual              | Fixation square           | -0.6 cpd   | 200      | 642      | 0.06 | 2              | none          | Fz                     | rejection: EOG/EEG threshold exclusion                    |         | 70      | 0–512   | O1                | -1.86a         | 325b           | 250–400     |
| Tales_2002 [118]                  | 24 | Peripheral white vertical bars           | 0.68    | 2.20    | Black     | Visual              | Fixation square           | -0.6 cpd   | 200      | 642      | 0.06 | 2              | none          | Fz                     | rejection: EOG/EEG threshold exclusion                    |         | 70      | 0–512   | O2                | -3.40a         | 325b           | 250–400     |
| Heslenfeld_2003 [119]             | 14 | Peripheral vertical square-wave gratings | 16.00   | 5.60    | Black     | Visual              | Visuo-motor task          | 1.72 cpd   | 17       | 433      | 0.20 | 1              | Reverse roles | Average mastoids       | correction: corrected via EOG regression                  | 0.08    | 35      | 60–452  | Oz                | -1.10          | 150b           | 100–200     |
| Kenemans_2003 [120]               | 12 | Peripheral vertical square-wave gratings | 5.40    | 5.20    | Black     | Visual              | Fixation cross            | 1.8 cpd    | 17       | 450      | 0.20 | Deviant alone  | none          | Right mastoid          | correction: corrected via EOG regression                  | 0.05    | 40      | 50–250  | Oz                | -1.19a         | 140a           | 60–200      |
| Stagg_2004 [56]                   | 12 | Peripheral white vertical bars           | 0.34    | 2.23    | Black     | Visual              | Fixation square           | 0.6 cpd    | 200      | 642      | 0.06 | Reverse roles  | none          | Fz                     | rejection: EOG/EEG threshold exclusion                    | 0.05    | 100     | 0–512   | Occipital         | -3.73a         | 305b           | 210–400     |
| Mackawa_2005 [57]                 | 7  | Central windmill-pattern                 | 5.80    | 5.80    | Grey      | Auditory and visual | Story and target windmill | 18 vanes   | 200      | 800      | 0.10 | Reverse roles  | none          | Nose-tip               | rejection: EOG/EEG threshold exclusion                    | 0.05    | 50      | 72–542  | Oz                | -3.47a         | 245a           | 230–320     |
| Tales_2006 [121]                  | 10 | Peripheral white vertical bars           | 0.68    | 2.20    | Black     | Visual              | Fixation square           | +0.6 cpd   | 200      | 642      | 0.06 | 2              | none          | Fz                     | rejection: EOG/EEG threshold exclusion                    |         | 70      | 0–512   | T6(P8)            | -3.90a         | 300b           | 250–400     |
| Tales_2008 [122]                  | 10 | Peripheral white vertical bars           | 0.68    | 2.20    | Black     | Visual              | Fixation square           | +0.6 cpd   | 200      | 642      | 0.06 | 2              | none          | Fz                     | rejection: EOG/EEG threshold exclusion                    |         | 70      | 0–512   | O2                | -0.63a         | 325b           | 250–400     |
| Mackawa_2009 [Experiment 1] [123] | 10 | Central windmill-pattern                 | 5.80    | 5.80    | Grey      | Auditory            | Story                     | 18 vanes   | 200      | 800      | 0.10 | Deviant block  | none          | EGI average [126, 127] | rejection: discarded epochs contaminated by EOG artifacts | 0.50    | 30      | 100–500 | Oz                | -6.33a         | 252a           | 150–300     |
| Mackawa_2009 [Experiment 2] [123] | 8  | Central windmill-pattern                 | 5.80    | 5.80    | Grey      | Auditory            | Story                     | 18 vanes   | 200      | 800      | 0.10 | Standard block | none          | EGI average [126, 127] | rejection: discarded epochs contaminated by EOG artifacts | 0.50    | 30      | 100–500 | Oz                | -2.19a         | 232a           | 150–300     |
| Kenemans_2010 [124]               | 16 | Peripheral vertical square-wave gratings | 5.40    | 5.20    | Black     | Visual              | Fixation cross            | 1.8 cpd    | 17       | 450      | 0.10 | Reverse roles  | none          | Right mastoid          | rejection: EOG/EEG threshold exclusion                    | 0.05    | 30      | 50–550  | Oz                | -0.90a         | 160b           | 150–170     |
| Chang_2011 [125]                  | 14 | Peripheral white vertical bars           | 0.34    | 2.23    | Black     | Visual              | Fixation square           | 0.6 cpd    | 200      | 612      | 0.12 | 2              | Reverse roles | Equi-probable          | correction: corrected via EOG regression                  | 0.10    | 30      | 100–500 | Parieto-occipital | -1.25a         | 200b           | 150–250     |
| Mackawa_2011 [126]                | 9  | Central windmill-pattern                 | 5.80    | 5.80    | Grey      | Auditory            | Story                     | 18 vanes   | 200      | 800      | 0.10 | Reverse roles  | none          | EGI average [126, 127] | rejection: discarded epochs contaminated by EOG artifacts | 0.50    | 30      | 100–500 | Oz                | -2.40          | 274            | 150–350     |
| Sulyk_2011 [69]                   | 12 | Peripheral Gabor patches                 | 0.80    | 0.80    | Black     | Visual              | Spaceship                 | 4 cpd      | 80       | 480      | 0.18 | Reverse roles  | none          | Linked-mastoids        | rejection: EOG/EEG threshold exclusion                    | 0.10    | 30      | 100–400 | Oz                | -1.18          | 136            | 135–145     |
| Stothart_2013a [127]              | 17 | Peripheral white vertical bars           | 10.50   | 10.50   | White     | Visual              | Small Blue Frame          | 0.6 cpd    | 200      | 642      | 0.18 | 2              | none          | Average                | correction: BESA automatic artifact correction            |         | 40      | 100–500 | Parieto-occipital | -1.15a         | 230a           | 170–264     |
| Stothart_2013b [128]              | 39 | Peripheral white vertical bars           | 1.37    | 4.47    | Black     | Visual              | Fixation square           | 0.6 cpd    | 200      | 642      | 0.06 | 2              | none          | Average                | correction: BESA automatic artifact correction            |         | 40      | 300–600 | Parieto-occipital | -0.66a         | 222a           | 100–600     |
| Mackawa_2013 [129]                | 20 | Central windmill-pattern                 | 5.80    | 5.80    | Grey      | Auditory            | Story                     | 18 vanes   | 200      | 800      | 0.10 | Reverse roles  | none          | EGI average [126, 127] | rejection: EOG/EEG threshold exclusion                    | 0.05    | 30      | 100–500 | Oz                | -1.25a         | 280b           | 150–350     |

(Continued)

Table 1. (Continued)

| Study                                        | N  | SOI                                                 | W<br>(°VA) | H<br>(°VA) | BG Colour | Task<br>Modality | Attention On            | D-S                        | SOI<br>(ms) | ISI<br>(ms) | D%<br>s | PC                                       | AC                | Ref                 | Ocular-artifact<br>correction                                           | HP<br>(Hz)                                              | LP<br>(Hz) | Epoch         | ROI                           | mean<br>vMMN<br>(µV) | peak<br>vMMN<br>(ms) | Time-<br>window |         |
|----------------------------------------------|----|-----------------------------------------------------|------------|------------|-----------|------------------|-------------------------|----------------------------|-------------|-------------|---------|------------------------------------------|-------------------|---------------------|-------------------------------------------------------------------------|---------------------------------------------------------|------------|---------------|-------------------------------|----------------------|----------------------|-----------------|---------|
| Cleary_2013 [130]                            | 20 | Background<br>horizontal<br>square-wave<br>gratings | 10.88      | 14.48      | Stimulus  | Visual           | Fixation<br>cross       | 6 cpd                      | 750         | 1,000       | 0.15    | none                                     | none              | Right<br>mastoid    | correction;<br>corrected via<br>EOG regression                          | 0.05                                                    | 30         | -200–<br>1000 | O1                            | -2.06a               | 162                  | 130–200         |         |
| Strohmer_2014 [131]                          | 26 | Peripheral white<br>vertical bars                   | 1.50       | 4.46       | Black     | Visual           | Fixation<br>square      | 0.6 cpd                    | 200         | 642         | 0.06    | none                                     | none              | Average             | correction;<br>BESA automatic<br>artifact<br>correction                 |                                                         | 40         | -100–<br>500  | Left<br>parieto-<br>occipital | -1.25a               | 195a                 | 170–250         |         |
| Hedge_2015 [Deviant 1] [132]                 | 20 | Peripheral<br>vertical square-<br>wave gratings     | 0.34       | 2.23       | Black     | Visual           | Fixation<br>square      | +0.6 cpd                   | 200         | 700         | 0.06    | 2                                        | Reverse<br>roles  | none                | Average                                                                 | correction;<br>BESA automatic<br>artifact<br>correction | 40         | -100–<br>600  | Parieto-<br>occipital         | -0.94                | 265b                 | 161–329         |         |
| Hedge_2015 [Deviant 2] [132]                 | 20 | Peripheral<br>vertical square-<br>wave gratings     | 0.34       | 2.23       | Black     | Visual           | Fixation<br>square      | -0.6 cpd                   | 200         | 700         | 0.06    | 2                                        | Reverse<br>roles  | none                | Average                                                                 | correction;<br>BESA automatic<br>artifact<br>correction | 40         | -100–<br>600  | Parieto-<br>occipital         | -0.22                |                      | 161–329         |         |
| File_2017 [Experiment 2] [86]                | 23 | Central<br>windmill-pattern                         | 13.82      | 13.82      | Grey      | Visual           | Spaceship               | 6 vane                     | 200         | 800         | 0.10    | 7                                        | Reverse<br>roles  | Equi-<br>probable   | Average                                                                 | rejection; EOG/<br>EEG threshold<br>exclusion           | 0.10       | 30            | -100–<br>400                  | Occipital            | -1.49                | 269             | 200–340 |
| Bodnar_2017 [87]                             | 19 | Central windmill<br>pattern                         | 13.82      | 13.82      | Grey      | Visual           | Centre<br>tracking task | 6 vane                     | 100         | 400         | 0.12    |                                          | Reverse<br>roles  | none                | Nose-tip                                                                | rejection; EOG/<br>EEG threshold<br>exclusion           | 0.10       | 30            | -100–<br>400                  | Occipital            | -1.73                | 203             | 198–218 |
| Male_2020 [Experiment 2] [34]                | 24 | Central Gabor<br>patches                            | 3.00       | 3.00       | Grey      | Visual           | Fixation dot            | 0.3 cpd                    | 100         | 400         | 0.13    | 1                                        | Cascadic          | Cascadic            | Nose-tip                                                                | correction; ICA<br>+ Eye-tracking                       | 0.10       | 40            | -100–<br>400                  | P8                   | 1.16                 |                 | 200–250 |
| Dang_2023 [133]                              | 31 | Peripheral<br>windmill-<br>patterns                 |            |            | Grey      | Visual           | Fixation<br>cross       | +6 vane                    | 300         | 600         | 0.20    |                                          | none              | Average             | correction; ICA                                                         | 1.00                                                    | 30         | -200–<br>500  | O2                            | -0.91a               | 257a                 | 230–330         |         |
| Molnar_2024 [Deviant 1] [134]                | 39 | Central<br>windmill-pattern                         | 32.28      | 16.14      | Grey      | Visual           | Spaceship               | +6 vane                    | 200         | 600         | 0.16    | 3                                        | Reverse<br>roles  | Average             | rejection;<br>eliminated by<br>ADJUST plugin                            | 0.03                                                    | 40         | -100–<br>600  | Right<br>occipital            | 0.15a                | 180b                 | 160–200         |         |
| Molnar_2024 [Deviant 2] [134]                | 39 | Central<br>windmill-pattern                         | 32.28      | 16.14      | Grey      | Visual           | Spaceship               | -6 vane                    | 200         | 600         | 0.16    | 3                                        | Reverse<br>roles  | Average             | rejection;<br>eliminated by<br>ADJUST plugin                            | 0.03                                                    | 40         | -100–<br>600  | Right<br>occipital            | 0.08a                |                      | 260–300         |         |
| Colour                                       |    |                                                     |            |            |           |                  |                         |                            |             |             |         |                                          |                   |                     |                                                                         |                                                         |            |               |                               |                      |                      |                 |         |
| Horimoto_2002 [135]                          | 11 | Central coloured<br>square                          |            |            |           | Auditory         | Tones                   | blue-green blue            | 1,000       | 1,750       | 0.10    | none                                     | none              | Linked-<br>earlobes | rejection; EOG/<br>EEG threshold<br>exclusion<br>+ visual<br>inspection | 0.05                                                    | 50         | -100–<br>900  | Pz                            | -4.80                | 250                  | 0–550           |         |
| Czigler_2002 [Deviant 1] [58]                | 8  | Peripheral<br>square-wave<br>grating                | 10.90      | 14.50      | Stimulus  | Visual           | Fixation<br>cross       | red-pink                   | 17          | 450         | 0.12    | Reverse<br>roles                         | Equi-<br>probable | Nose-tip            | rejection; EOG/<br>EEG threshold<br>exclusion                           | 0.10                                                    | 30         | -100–<br>650  | Occipital                     | -0.07a               |                      | 128–142         |         |
| Czigler_2002 [Deviant 2] [136]               | 8  | Peripheral<br>square-wave<br>grating                | 10.90      | 14.50      | Stimulus  | Visual           | Fixation<br>cross       | red-green                  | 17          | 450         | 0.12    | Reverse<br>roles                         | Equi-<br>probable | Nose-tip            | rejection; EOG/<br>EEG threshold<br>exclusion                           | 0.10                                                    | 300        | -100–<br>650  | Occipital                     | -0.36a               | 136                  | 128–142         |         |
| Czigler_2004 [137]                           | 12 | Peripheral<br>coloured-black<br>checkerboard        |            |            | Dark      | Visual           | Fixation<br>cross       | green-red                  | 17          | 400         | 0.10    | Reverse<br>roles                         | none              | Linked-<br>mastoids | none                                                                    | 0.10                                                    | 30         | -100–<br>450  | Oz                            | -1.36                | 170b                 | 140–200         |         |
| Mao_2005 [138]                               | 25 | Central coloured<br>dots                            | 2.86       | 2.86       | Black     | Visual           | Dot colour              | red-green,<br>purple-white | 300         | 700         | 0.25    | none                                     | none              | Linked-<br>earlobes | rejection;<br>excluded trials<br>containing EOG<br>artifacts            | 0.05                                                    | 100        | -200–<br>2200 | P3                            | -3.00a               | 304                  | 250–350         |         |
| Kimura_2006 [139]                            | 12 | Peripheral discs                                    | 2.50       | 2.50       | Black     | Visual           | Fixation<br>shape       | red-blue                   | 70          | 350         | 0.20    | Reverse<br>roles and<br>deviant<br>block | none              | Nose-tip            | rejection; EOG/<br>EEG threshold<br>exclusion                           | 0.10                                                    | 30         | -50–<br>400   | PO8                           | -1.29a               | 160b                 | 150–170<br>[58] |         |
| Czigler_2007 [Experiment 1: long ISI] [140]  | 11 | Peripheral<br>coloured-black<br>checkerboard        | 8.07       | 6.06       | Stimulus  | Visual           | Fixation<br>cross       | green-red                  | 14          | 160         | 0.20    | none                                     | none              | Nose-tip            | rejection; EOG/<br>EEG threshold<br>exclusion                           | 0.15                                                    | 30         | -50–<br>300   | Oz                            | -1.32                | 132                  | 112–152         |         |
| Czigler_2007 [Experiment 1: short ISI] [140] | 11 | Peripheral<br>coloured-black<br>checkerboard        | 8.07       | 6.06       | Stimulus  | Visual           | Fixation<br>cross       | green-red                  | 14          | 0           | 0.20    | none                                     | none              | Nose-tip            | rejection; EOG/<br>EEG threshold<br>exclusion                           | 0.15                                                    | 30         | -50–<br>300   | Oz                            | -0.46                |                      | 112–152         |         |
| Czigler_2007 [Experiment 2: short ISI] [140] | 11 | Peripheral<br>coloured-black<br>checkerboard        | 8.07       | 6.06       | Stimulus  | Visual           | Fixation<br>cross       | green-red                  | 14          | 26          | 0.20    | none                                     | none              | Nose-tip            | rejection; EOG/<br>EEG threshold<br>exclusion                           | 0.15                                                    | 30         | -50–<br>300   | Oz                            | -1.06                | 124                  | 104–144         |         |
| Czigler_2007 [Experiment 2: short ISI] [140] | 11 | Peripheral<br>coloured-black<br>checkerboard        | 8.07       | 6.06       | Stimulus  | Visual           | Fixation<br>cross       | green-red                  | 14          | 13          | 0.20    | none                                     | none              | Nose-tip            | rejection; EOG/<br>EEG threshold<br>exclusion                           | 0.15                                                    | 30         | -50–<br>300   | Oz                            | 0.19                 |                      | 104–144         |         |

(Continued)

Table 1. (Continued)

| Study                               | N  | SOI                        | W<br>(°VA) | H<br>(°VA) | BG Colour | Task<br>Modality | Attention On                  | D-S                      | SOI<br>(ms) | ISI<br>(ms) | D%<br>S | PC | AC            | Ref              | Ocular-artifact<br>correction                          | HP<br>(Hz) | LP<br>(Hz) | Epoch     | ROI                    | mean<br>vMMN<br>(µV) | peak<br>vMMN<br>(ms) | Time-<br>window |
|-------------------------------------|----|----------------------------|------------|------------|-----------|------------------|-------------------------------|--------------------------|-------------|-------------|---------|----|---------------|------------------|--------------------------------------------------------|------------|------------|-----------|------------------------|----------------------|----------------------|-----------------|
| Liu_2008 [141]                      | 15 | Central red square         | 3.70       | 3.70       | Grey      | Visual           | Target flower image           | red-lighter red          | 100         | 900         | 0.20    | 2  | none          | Nose-tip         | rejection: EOG/EEG threshold exclusion                 | 0.05       | 30         | -100–600  | Posterior areas        | -0.59                | 179                  | 110–180         |
| Grimm_2009 [142]                    | 16 | Peripheral green triangles | 4.20       | 3.40       | Grey      | Visual           | Fixation target               | green-red                | 150         | 1,450       | 0.11    | 2  | Reverse roles | Nose-tip         | rejection: EOG/EEG threshold exclusion                 | 0.75       | 35         | -100–900  | Right occipital        | -0.87                | 280b                 | 265–295         |
| Thierry_2009 [143]                  | 20 | Central disc               | 2.00       | 2.00       | Grey      | Visual           | Shape change                  | green-green or blue-blue | 200         | 800         | 0.10    | 3  | Reverse roles | Average          | correction: EOG mathematical correction                | 0.10       | 20         | -100–1000 | Parieto-occipital      | -0.91a               | 197a                 | 162–232         |
| Berti_2009 [144]                    | 8  | Peripheral triangle        |            |            | Grey      | Visual           | Triangle orientation          | red-green                | 200         | 1,100       | 0.18    | 3  | Reverse roles | Nose-tip         | rejection; excluded epochs with excessive EOG activity | 1.00       | 25         | -200–400  | P3                     | 0.52a                |                      | 150–210         |
| Czajka_2010 [68]                    | 24 | Peripheral line segments   | 0.04       | 0.37       | Grey      | Visual           | Central line segment          | turquoise-yellow-green   | 70          | 280         | 0.15    |    | Reverse roles | Average mastoids | rejection: EOG/EEG threshold exclusion                 | 0.15       | 30         | -100–500  | POz                    | -0.60                | 141                  | 137–145         |
| Clifford_2010 [Deviant 1] [27]      | 18 | LoVF Peripheral squares    | 4.09       | 4.09       | Grey      | Visual           | Fixation cross                | blue-blue                | 200         | 1,200       | 0.20    | 1  | none          | Average earlobes | rejection: EOG threshold exclusion                     | 0.10       | 40         | -100–700  | Posterior              | -0.27a               |                      | 100–250         |
| Clifford_2010 [Deviant 2] [27]      | 18 | LoVF Peripheral squares    | 4.09       | 4.09       | Grey      | Visual           | Fixation cross                | blue-green               | 200         | 1,200       | 0.20    | 1  | none          | Average earlobes | rejection: EOG threshold exclusion                     | 0.10       | 40         | -100–700  | Posterior              | -1.76a               | 200b                 | 100–250         |
| Mo_2011 [145]                       | 30 | Peripheral squares         | 2.50       | 2.50       | Grey      | Visual           | Fixation cross                | blue-green               | 200         | 900         | 0.20    |    | Reverse roles | Nose-tip         | correction: EOG mathematical correction                | 0.80       | 20         | -100–800  | Parieto-occipital      | -1.03a               | 160                  | 130–190         |
| Stefanics_2011 [Experiment 1]       | 13 | Peripheral discs           |            |            | Grey      | Visual           | Fixation cross                | red-green                | 100         | 800         | 0.10    |    | Reverse roles | Average          | rejection: EOG/EEG threshold exclusion                 | 0.10       | 30         | -100–500  | Occipital              | -0.66                | 248a                 | 232–254         |
| Stefanics_2011 [Experiment 2]       | 15 | Peripheral discs           |            |            | Grey      | Visual           | Fixation cross                | red-green                | 100         | 800         | 0.20    |    | Reverse roles | Average          | rejection: EOG/EEG threshold exclusion                 | 0.10       | 30         | -100–500  | Occipital              | -1.16                | 214a                 | 142–286         |
| Müller_2012 [146]                   | 15 | LoVF Peripheral squares    | 0.92       | 0.92       | Grey      | Visual           | Fixation cross                | green-red                | 120         | 600         | 0.10    | 1  | Reverse roles | Nose-tip         | rejection: EOG/EEG threshold exclusion                 | 1.00       | 35         | -100–600  | Occipital              | -1.57                | 260                  | 240–280         |
| Shi_2013 [73]                       | 12 | Peripheral red rectangles  | 0.10       | 0.30       | White     | Visual           | Fixation cross                | red-blue                 | 50          | 550         | 0.10    | 1  | none          | Nose-tip         | correction; corrected via EOG regression               | 0.10       | 100        | -100–400  | Occipito-temporal      | -0.39a               | 200a                 | 150–250         |
| Wu_2013 [147]                       | 12 | Peripheral rectangles      | 3.44       | 1.15       |           | Visual           | Central number task           | red-green                | 50          | 550         | 0.10    | 1  | none          | Nose-tip         | correction: EOG artifact correction                    | 0.10       | 100        | -100–400  |                        |                      | 164                  | 150–200         |
| He_2014 [Deviant 1] [148]           | 12 | Peripheral green circles   | 4.20       | 4.20       | White     | Visual           | Fixation cross                | green-sea-green          | 100         | 400         | 0.09    | 2  | none          | Nose-tip         | correction; corrected via EOG regression               | 0.05       | 30         | -50–400   | Left parieto-occipital | -2.03                | 187a                 | 172–194         |
| He_2014 [Deviant 2] [148]           | 12 | Peripheral green circles   | 4.20       | 4.20       | White     | Visual           | Fixation cross                | green-sea-green          | 100         | 400         | 0.09    | 2  | none          | Nose-tip         | correction; corrected via EOG regression               | 0.05       | 30         | -50–400   | Left parieto-occipital | 0.06                 |                      | 172–194         |
| Zhong_2015 [Deviant 1 RVF] [149]    | 26 | RVF Peripheral squares     | 1.27       | 1.27       | Grey      | Visual           | Fixation cross                | BLUE-GREEN               | 200         | 900         | 0.20    | 1  | none          | Nose-tip         | correction: EOG mathematical correction                | 0.80       | 20         | -100–800  | Parieto-occipital      | -0.46a               | 160                  | 130–190         |
| Zhong_2015 [Deviant 2 RVF] [149]    | 26 | RVF Peripheral squares     | 1.27       | 1.27       | Grey      | Visual           | Fixation cross                | blue-green               | 200         | 900         | 0.20    | 1  | none          | Nose-tip         | correction: EOG mathematical correction                | 0.80       | 20         | -100–800  | Parieto-occipital      | -0.09a               |                      | 130–190         |
| Zhong_2015 [Deviant 1 LVF] [149]    | 26 | LVF Peripheral squares     | 1.27       | 1.27       | Grey      | Visual           | Fixation cross                | BLUE-GREEN               | 200         | 900         | 0.20    | 1  | none          | Nose-tip         | correction: EOG mathematical correction                | 0.80       | 20         | -100–800  | Parieto-occipital      | -0.18a               |                      | 130–190         |
| Zhong_2015 [Deviant 2 LVF] [149]    | 26 | LVF Peripheral squares     | 1.27       | 1.27       | Grey      | Visual           | Fixation cross                | blue-green               | 200         | 900         | 0.20    | 1  | none          | Nose-tip         | correction: EOG mathematical correction                | 0.80       | 20         | -100–800  | Parieto-occipital      | -0.18a               |                      | 130–190         |
| Sysoeva_2015 [UVF short ISI] [150]  | 12 | UVF Peripheral discs       | 4.23       | 4.23       | Black     | Visual           | Line orientation within discs | red-green                | 1,100       |             | 0.10    |    | Reverse roles | Linked mastoids  | rejection: EOG/EEG threshold exclusion                 | 1.00       | 30         | -100–500  | O1                     | -1.01a               | 141                  | 120–160         |
| Sysoeva_2015 [LoVF short ISI] [150] | 12 | LoVF Peripheral discs      | 4.23       | 4.23       | Black     | Visual           | Line orientation within discs | red-green                | 1,100       |             | 0.10    |    | Reverse roles | Linked mastoids  | rejection: EOG/EEG threshold exclusion                 | 1.00       | 30         | -100–500  | O1                     | -0.21a               |                      | 120–160         |
| Sysoeva_2015 [UVF long ISI] [150]   | 12 | UVF Peripheral discs       | 4.23       | 4.23       | Black     | Visual           | Line orientation within discs | red-green                | 1,610       |             | 0.10    |    | Reverse roles | Linked mastoids  | rejection: EOG/EEG threshold exclusion                 | 1.00       | 30         | -100–500  | O1                     | -0.13a               |                      | 120–160         |

(Continued)

Table 1. (Continued)

| Study                                      | N  | SOI                                             | W (°A) | H (°A) | BG Colour | Task Modality       | Attention On                      | D-S                            | SOI (ms) | ISI (ms)     | D% S | PC            | AC            | Ref             | Ocular-artifact correction                              | HP (Hz)                            | LP (Hz) | Epoch    | ROI                     | mean vMMN (µV) | peak vMMN (ms) | Time-window |         |
|--------------------------------------------|----|-------------------------------------------------|--------|--------|-----------|---------------------|-----------------------------------|--------------------------------|----------|--------------|------|---------------|---------------|-----------------|---------------------------------------------------------|------------------------------------|---------|----------|-------------------------|----------------|----------------|-------------|---------|
| Sysawa_2015 [LoVF long ISI] [150]          | 12 | LoVF Peripheral discs                           | 4.23   | 4.23   | Black     | Visual              | Line orientation within discs     | red-green                      |          | <b>1,610</b> | 0.10 | Reverse roles | none          | Linked-mastoids | rejection: EOG/EEG threshold exclusion                  | 1.00                               | 30      | -100–500 | O1                      | <b>-0.10a</b>  |                | 120–160     |         |
| Li_2017 [85]                               | 12 | Peripheral polygons                             | 0.57   | 1.70   | Grey      | Manual              | Visuo-motor task                  | green-red                      | 50       | 600          | 0.17 | 1             | Equi-probable |                 | correction; removed influence of EOG on other leads     |                                    |         | -100–400 | Right occipito-temporal | 0.43a          | 224a           | 175–225     |         |
| Maciejewska_2017 [151]                     | 9  | Central checkerboards                           |        |        | Stimulus  | Visual              | Fixation cross                    | red-green/ additional stimulus | 20       | 400          | 0.10 | 4             | Equi-probable | AFz             | rejection: EOG/EEG threshold exclusion                  | 1.00                               | 30.0    | -100–400 | Cp1                     | -1.18          | 165b           | 160–170     |         |
| Stefanics_2018 [152]                       | 34 | Peripheral faces                                | 3.80   | 5.40   | Grey      | Visual              | Fixation cross                    | red-green                      | 200      | <b>700</b>   | 0.50 | 5             | Reverse roles | Average         | correction; BESA automatic artifact correction          | 0.05                               | 30      | -100–500 | Occipito-temporal       | -0.64a         | 200a           | 196–228     |         |
| Hilger_2023 [153]                          | 50 | Peripheral matrix of discs                      | 9.76   | 8.82   | Black     | Visual              | Fixation cross                    | red-green                      | 300      | 300          | 0.20 | 1             | Reverse roles | Average         | rejection: EOG threshold exclusion                      | 0.10                               | 10      | -100–400 | POz                     | -0.12          | 221a           | 125–275     |         |
| Suzuki_2024 [154]                          | 39 | Five Chevrons                                   | 11.42  | 2.43   | Grey      | Visual              | Middle chevron orientation        | black-red                      | 100      | <b>1,500</b> | 0.20 | 1             | Reverse roles | Nose-tip        | correction; ICA                                         | 0.10                               | 50      | -100–800 | Posterior clusters      | -0.85          | 205b           | 180–230     |         |
| Qian_2014 [29]                             | 14 | Peripheral red rectangles                       | 0.10   | 0.30   | White     | Visual              | Fixation cross                    | red-blue                       | 50       | 550          | 0.10 | 1             | none          | Nose-tip        | rejection: EOG/EEG threshold exclusion                  | 0.10                               | 100     | -100–500 | Occipito-temporal       | -1.11          | 205a           | 150–250     |         |
| Size/Shape                                 |    |                                                 |        |        |           |                     |                                   |                                |          |              |      |               |               |                 |                                                         |                                    |         |          |                         |                |                |             |         |
| Czigler_1990 [No attention condition] [61] | 9  | Chevrons within rectangular frame               | 1.27   | 0.77   |           | Visual              | Central chevrons                  | +Frame thickness               | 83       | 417          | 0.20 | 2             | none          | none            | Linked-earlobes                                         | rejection: EOG threshold exclusion | 0.20    | 50.0     | 0–768                   | Oz             | <b>-0.09a</b>  |             | 210–270 |
| Czigler_1990 [Attention condition] [61]    | 9  | Chevrons within rectangular frame               | 1.27   | 0.77   |           | Visual              | Frame deviants                    | +Frame thickness               | 83       | 417          | 0.20 | 2             | none          | none            | Linked-earlobes                                         | rejection: EOG threshold exclusion | 0.20    | 50       | 0–768                   | Oz             | <b>-1.91a</b>  |             | 210–270 |
| Woods_1992 [Attention condition] [155]     | 12 | Peripheral vertical gratings                    | 3.90   | 4.40   | Black     | Visual              | Visual deviants                   | -0.80° height                  | 50       | <b>400</b>   | 0.10 | none          | none          | Non-cephalic    | correction: EOG artifact correction +CCTV               | 0.10                               | 40      | -200–800 | PTc                     | -1.79a         | 260b           | 220–300     |         |
| Woods_1992 [No attention condition] [155]  | 12 | Peripheral vertical gratings                    | 3.90   | 4.40   | Black     | Auditory and Visual | Auditory deviants                 | -0.80° height                  | 50       | <b>400</b>   | 0.10 | none          | none          | Non-cephalic    | correction: EOG artifact correction +CCTV               | 0.10                               | 40      | -200–800 | PTc                     | <b>-0.56a</b>  |                | 230–330     |         |
| Alho_1992 [26]                             | 12 | Central white vertical gratings                 | 3.90   | 4.40   | Black     | Auditory and Visual | Deviants                          | -0.50° height                  | 50       | <b>400</b>   | 0.20 |               | none          | Non-cephalic    | rejection; excluded trials with excessive eye movements | 0.10                               | 40      | -200–800 | Oz                      | -2.00a         | 120            | 90–290      |         |
| Kaplan_2007 [No attention condition] [156] | 13 | Peripheral pattern of red light-emitting diodes | 9.20   | 18.20  |           | Visual              | Fixation red light-emitting diode | -4.6° width                    |          |              | 0.14 |               | none          | Linked-earlobes | none                                                    |                                    |         | -100–700 | P4                      | <b>0.00</b>    |                | 340–460     |         |
| Kaplan_2007 [Attention condition] [156]    | 13 | Peripheral pattern of red light-emitting diodes | 9.20   | 18.20  |           | Visual              | Fixation red light-emitting diode | -4.6° width                    |          |              | 0.14 |               | none          | Linked-earlobes | none                                                    |                                    |         | -100–700 | P4                      |                | 400            | 340–460     |         |
| Kimura_2008 [Deviant 1] [157]              | 12 | Peripheral discs                                | 1.70   | 1.70   | Black     | Visual              | Fixation target                   | +0.9° diameter                 | 200      | 1,600        | 0.16 |               | none          | Nose-tip        | rejection: EOG/EEG threshold exclusion                  | 0.03                               | 30      | -100–900 | Oz                      | -1.69a         | 130b           | 120–140     |         |
| Kimura_2008 [Deviant 2] [157]              | 12 | Peripheral discs                                | 1.70   | 1.70   | Black     | Visual              | Fixation target                   | -0.9° diameter                 | 200      | 1,600        | 0.16 |               | none          | Nose-tip        | rejection: EOG/EEG threshold exclusion                  | 0.03                               | 30      | -100–900 | Oz                      | <b>0.01a</b>   |                | 120–140     |         |
| Grimm_2009 [142]                           | 16 | Peripheral green triangles                      | 4.20   | 3.40   | Grey      | Visual              | Fixation target                   | Hexagon                        | 150      | 1,450        | 0.11 | 2             | Reverse roles | Nose-tip        | rejection: EOG/EEG threshold exclusion                  | 0.75                               | 35      | -100–900 | Right occipital         | -0.70          | 260b           | 245–275     |         |
| Freyen_2010 [58]                           | 16 | Central letter                                  | 1.20   | 0.80   | Black     | Visual              | Target image                      | letter-non-letter              | 500      | 750          | 0.10 |               | none          | Nose-tip        | correction; corrected for vertical eye movements        | 1.00                               | 30      | -50–800  | Oz                      | -3.30          | 273            | 248–334     |         |
| Bubrowský_2011 [159]                       | 10 | Central 'O'                                     |        |        |           | Visual              | Fixation target                   | 'X'                            | 200      | <b>1,200</b> | 0.10 |               | none          |                 | rejection; inspection for artifacts exclusion           | 0.10                               | 45      | -100–700 | Posterior               |                | 208b           | 185–232     |         |

(Continued)

Table 1. (Continued)

| Study                              | N  | SOI                                                   | W<br>(°VA) | H<br>(°VA) | BG Colour | Task<br>Modality          | Attention On             | D-S                             | SOI<br>(ms) | ISI<br>(ms) | D%<br>S | PC                            | AC                            | Ref                 | Ocular-artifact<br>correction                                   | HP<br>(Hz) | LP<br>(Hz) | Epoch       | ROI                                         | mean<br>vMMN<br>(µV) | peak<br>vMMN<br>(ms) | Time-<br>window |
|------------------------------------|----|-------------------------------------------------------|------------|------------|-----------|---------------------------|--------------------------|---------------------------------|-------------|-------------|---------|-------------------------------|-------------------------------|---------------------|-----------------------------------------------------------------|------------|------------|-------------|---------------------------------------------|----------------------|----------------------|-----------------|
| Cléry_2013 [160]                   | 13 | Central ellipse                                       | 2.00       | 2.00       | Black     | Visual                    | Fixation<br>cross        | Horizontal-<br>vertical ellipse | 140         | 650         | 0.18    | Reverse<br>roles              | none                          | Nose-tip            | correction;<br>NeuroScan<br>spatial filter<br>transform         | 0.30       | 70         | 100-<br>600 | Right<br>occipito-<br>parietal-<br>temporal | -1.60                | 210                  | 180-240         |
| Shi_2013 [Shape deviant]<br>[73]   | 12 | Peripheral red<br>rectangles                          | 0.10       | 0.30       | White     | Visual                    | Fixation<br>cross        | red-ellipses                    | 50          | 550         | 0.10    | 1                             | none                          | Nose-tip            | corrected via<br>EOG regression                                 | 0.10       | 100        | 100-<br>400 | Occipito-<br>temporal                       | -1.00a               | 180a                 | 150-250         |
| Shi_2013 [Size deviant]<br>[73]    | 12 | Peripheral red<br>rectangles                          | 0.10       | 0.30       | White     | Visual                    | Fixation<br>cross        | +0.06° width                    | 50          | 550         | 0.10    | 1                             | none                          | Nose-tip            | correction;<br>corrected via<br>EOG regression                  | 0.10       | 100        | 100-<br>400 | Occipito-<br>temporal                       | -0.60                | 190a                 | 150-250         |
| Wu_2013 [Shape deviant]<br>[74]    | 12 | Peripheral<br>rectangles                              | 3.44       | 1.15       |           | Visual                    | Central<br>number task   | circle                          | 50          | 550         | 0.10    | 1                             | none                          | Nose-tip            | correction; EOG<br>artifact<br>correction                       | 0.10       | 100        | 100-<br>400 |                                             |                      | 174                  | 150-200         |
| Wu_2013 [Size deviant]<br>[74]     | 12 | Peripheral<br>rectangles                              | 3.44       | 1.15       |           | Visual                    | Central<br>number task   | width                           | 50          | 550         | 0.10    | 1                             | none                          | Nose-tip            | correction; EOG<br>artifact<br>correction                       | 0.10       | 100        | 100-<br>400 |                                             |                      | 162                  | 150-200         |
| Bottau_2014 [161]                  | 12 | Circle                                                | 2.00       | 2.00       | Black     | Visual                    | Fixation<br>cross        | circle-ellipse                  | 107         | 580         | 0.14    | 3                             | Reverse<br>roles              | Nose-tip            | correction; ICA                                                 | 0.10       | 40         | 200-<br>600 | Right<br>posterior                          | -0.64a               | 193                  | 157-292         |
| Qian_2014 [Shape<br>deviant] [79]  | 14 | Peripheral red<br>rectangles                          | 0.10       | 0.30       | White     | Visual                    | Fixation<br>cross        | rectangles-<br>ellipses         | 50          | 550         | 0.10    | 1                             | none                          | Nose-tip            | rejection; EOG/<br>EEG threshold<br>exclusion                   | 0.10       | 100        | 100-<br>500 | Occipito-<br>temporal                       | -0.64                | 200a                 | 150-250         |
| Qian_2014 [Size deviant]<br>[79]   | 14 | Peripheral red<br>rectangles                          | 0.10       | 0.30       | White     | Visual                    | Fixation<br>cross        | +0.06° width                    | 50          | 550         | 0.10    | 1                             | none                          | Nose-tip            | rejection; EOG/<br>EEG threshold<br>exclusion                   | 0.10       | 100        | 100-<br>500 | Occipito-<br>temporal                       | -0.55                | 180a                 | 150-250         |
| Li_2017 [85]                       | 12 | Peripheral<br>polygons                                | 0.57       | 1.70       | Grey      | Manual                    | Visuo-motor<br>task      | rectangle-<br>hexagon           | 50          | 600         | 0.17    | 1                             | Equi-<br>probable             |                     | correction;<br>removed<br>influence of<br>EOG on other<br>leads |            |            | 100-<br>400 | Right<br>occipito-<br>temporal              | 0.30a                | 220a                 | 175-225         |
| Maciejewska_2017 [151]             | 9  | Central<br>checkboards                                |            |            | Stimulus  | Visual                    | Fixation<br>cross        | +1.5°                           | 20          | 400         | 0.10    | 4                             | Equi-<br>probable             | AFz                 | rejection; EOG/<br>EEG threshold<br>exclusion                   | 1.00       | 300        | 100-<br>400 | POz                                         | -0.84                | 170b                 | 140-200         |
| Yu_2017 [Deviant 1]<br>[162]       | 23 | RVF Peripheral<br>novel polygons                      |            |            | White     | Visual                    | Fixation<br>cross        | Most different<br>polygon       | 200         | 900         | 0.20    | 1                             | none                          | Nose-tip            | rejection; EOG/<br>EEG threshold<br>exclusion                   | 0.80       | 40         | 100-<br>800 | Lateral<br>parieto-<br>occipital            | -0.76a               | 160b                 | 130-190         |
| Yu_2017 [Deviant 2]<br>[162]       | 23 | RVF Peripheral<br>novel polygons                      |            |            | White     | Visual                    | Fixation<br>cross        | Least different<br>polygon      | 200         | 900         | 0.20    | 1                             | none                          | Nose-tip            | rejection; EOG/<br>EEG threshold<br>exclusion                   | 0.80       | 40         | 100-<br>800 | Lateral<br>parieto-<br>occipital            | -0.10a               |                      | 130-190         |
| Kojouharova_2019 [163]             | 19 | Peripheral matrix<br>of black lines or<br>shapes      | 1.74       | 1.74       | Grey      | Visual                    | Central<br>tracking task | Shape-bar                       | 200         | 400         | 0.20    | 2                             | Reverse<br>Roles              | Average             | rejection; EOG/<br>EEG threshold<br>exclusion                   | 0.10       | 30         | 100-<br>500 | Oz                                          | -0.92a               | 124.4                | 122-178         |
| Schlossmacher_2020<br>[164]        | 52 | Peripheral white<br>lines forming<br>square/rectangle | 10.00      | 10.00      | Black     | Visual                    | Shape<br>omissions       | Square-<br>rectangle            | 100         | 700         | 0.10    | 4                             | Reverse<br>Roles              | Average             | rejection; visual<br>inspection                                 | 0.10       | 25         | 200-<br>600 | Posterior                                   | -0.57a               | 261a                 | 200-300         |
| Nie_2020 [165]                     | 30 | Peripheral Writ<br>symbols                            | 3.68       | 3.42       | White     | Visual                    | Fixation<br>cross        | rounded-<br>horizontal bars     | 100         | 500         | 0.20    | 3                             | Reverse<br>roles              | Nose-tip            | rejection; EOG/<br>EEG threshold<br>exclusion                   | 0.05       | 100        | 100-<br>500 | Occipital                                   | -0.44                | 220a                 | 180-300         |
| <b>Location</b>                    |    |                                                       |            |            |           |                           |                          |                                 |             |             |         |                               |                               |                     |                                                                 |            |            |             |                                             |                      |                      |                 |
| Berti_2004 [Experiment<br>1] [166] | 10 | Green square<br>with central grey<br>triangles        |            |            | Grey      | Visual                    | Stimulus<br>duration     | moved within<br>green square    | 200         | 1,100       | 0.12    | none                          | none                          | Nose-tip            | rejection;<br>excluded epochs<br>with excessive<br>EOG activity | 1.00       | 20         | 200-<br>400 | P8                                          | -1.19                | 224a                 | 220-300         |
| Berti_2004 [Experiment<br>2] [166] | 6  | Green square<br>with central grey<br>triangles        |            |            | Grey      | Visual                    | Stimulus<br>duration     | moved within<br>green square    | 200         | 1,100       | 0.12    | Equi-<br>probable             | Equi-<br>probable             | Nose-tip            | rejection;<br>excluded epochs<br>with excessive<br>EOG activity | 1.00       | 20         | 200-<br>400 | P8                                          | -1.50                | 245a                 | 220-300         |
| Nagai_2005 [167]                   | 14 | Four white<br>capital letters                         | 0.29       | 0.23       | Black     | Visual                    | Letters                  | 0.63° lateral<br>shift          | 150         | 40          | 0.33    | 2                             | none                          | Linked-<br>earlobes | rejection; visual<br>inspection                                 |            | 50         | 480-<br>800 | Pz                                          |                      | 350b                 | 300-400         |
| Berti_2006 [168]                   | 8  | Green square<br>with central grey<br>triangles        |            |            | Grey      | Visual                    | Stimulus<br>duration     | moved within<br>green square    | 200         | 1,300       | 0.12    | Position<br>Equi-<br>probable | Position<br>Equi-<br>probable | Nose-tip            | rejection;<br>excluded epochs<br>with excessive<br>EOG activity | 1.00       | 20         | 200-<br>600 | Posterior<br>occipital                      | -2.01                | 220                  | 170-300         |
| Grimm_2009 [142]                   | 16 | Peripheral green<br>triangles                         | 4.20       | 3.40       | Grey      | Visual                    | Fixation<br>target       | 2.4° Vertically<br>shifted      | 150         | 1,450       | 0.11    | 2                             | Reverse<br>roles              | Nose-tip            | rejection; EOG/<br>EEG threshold<br>exclusion                   | 0.75       | 35         | 100-<br>900 | Right<br>occipital                          | -0.93                | 245b                 | 230-260         |
| Boll_2009 [169]                    | 11 | Peripheral green<br>triangles                         |            |            | Grey      | Auditory<br>and<br>Visual |                          | 0.42° ↑                         | 200         | 1,700       | 0.19    | none                          | none                          | Nose-tip            | rejection; EOG/<br>EEG threshold<br>exclusion                   | 1.00       | 20         | 200-<br>800 | P8                                          | -0.86                | 200                  | 170-250         |

(Continued)

Table 1. (Continued)

| Study                           | N  | SOI                                       | W (°VA) | H (°VA) | BG Colour | Task Modality | Attention On                        | D-S                       | SOI (ms) | ISI (ms) | D%   | Min. S | PC            | AC            | Ref              | Ocular-artifact correction                              | HP (Hz) | LP (Hz) | Epoch    | ROI                     | mean vMMN (µV) | peak vMMN (ms) | Time-window |
|---------------------------------|----|-------------------------------------------|---------|---------|-----------|---------------|-------------------------------------|---------------------------|----------|----------|------|--------|---------------|---------------|------------------|---------------------------------------------------------|---------|---------|----------|-------------------------|----------------|----------------|-------------|
| Berti_2009 [Experiment 1] [144] | 8  | Peripheral green triangle                 |         |         | Grey      | Visual        | Triangle orientation                | Laterally shifted         | 200      | 1,300    | 0.18 | 3      | Reverse roles | none          | Nose-tip         | rejection; excluded epochs with excessive EOG activity  | 1.00    | 25      | -200–400 | P3                      | -2.74          | 190a           | 150–210     |
| Berti_2009 [Experiment 2] [144] | 8  | Central green triangle                    |         |         | Grey      | Visual        | Number task                         | Laterally shifted         | 200      | 1,300    | 0.18 | 3      | Reverse roles | none          | Nose-tip         | rejection; excluded epochs with excessive EOG activity  | 1.00    | 25      | -200–400 | P3                      | -2.37          | 200a           | 150–210     |
| Berti_2011 [170]                | 10 | Upper-case consonants                     |         |         | Grey      | Visual        | Target detection                    | Vertically shifted        | 100      |          | 0.40 | 5      | none          | none          | Nose-tip         | rejection; excluded epochs with excessive eye movements | 1.00    | 30      | -100–400 | O2                      | -2.36          | 280a           | 260–300     |
| He_2014 [148]                   | 12 | Peripheral green circles                  | 4.20    | 4.20    | White     | Visual        | Fixation cross                      | 90°                       | 100      | 400      | 0.09 | 2      | none          | none          | Nose-tip         | correction; corrected via EOG regression                | 0.05    | 30      | -50–400  | Right parieto-occipital | -3.54          | 199a           | 196–218     |
| Berti_2018 [1VF] [171]          | 12 | LVF Peripheral (2.86°) digits             |         |         | Grey      | Visual        | Fixation cross                      | Outward Peripherally      | 200      | 1,100    | 0.12 | 3      | none          | none          | Nose-tip         | rejection; excluded epochs with excessive EOG activity  | 1.00    | 25      | -200–600 | Right parieto-occipital | -0.41          |                | 200–250     |
| Berti_2018 [RVF] [171]          | 12 | RVF Peripheral (2.86°) digits             |         |         | Grey      | Visual        | Fixation cross                      | Outward Peripherally      | 200      | 1,100    | 0.12 | 3      | none          | none          | Nose-tip         | rejection; excluded epochs with excessive EOG activity  | 1.00    | 25      | -200–600 | Left parieto-occipital  | -0.65          | 225b           | 200–250     |
| <b>Motion</b>                   |    |                                           |         |         |           |               |                                     |                           |          |          |      |        |               |               |                  |                                                         |         |         |          |                         |                |                |             |
| Lorenzo-Lopez_2004 [172]        | 7  | Peripheral horizontal sinusoidal grating  | 4.13    | 4.13    |           | Visual        | Fixation number                     | 1.95°/s OD                | 133      | 665      | 0.20 | 1      | none          | none          | Nose-tip         | rejection; visual inspection                            | 0.10    | 30      | -100–700 | Parieto-occipital       | -2.26          | 180a           | 165–205     |
| Pazo-Alvarez_2004a [173]        | 7  | Peripheral sinusoidal grating             | 4.13    | 4.13    |           | Visual        | Fixation number                     | 1.95°/s OD                | 133      | 665      | 0.20 | 1      | Reverse roles | Equi-probable | Nose-tip         | rejection; EOG/EEG threshold exclusion                  | 0.10    | 30      | -100–700 | Occipital               | -1.78a         | 155b           | 145–165     |
| Pazo-Alvarez_2004b [174]        | 12 | Peripheral sinusoidal grating             | 4.13    | 4.13    |           | Visual        | Fixation number                     | 1.95°/s OD                | 133      | 665      | 0.20 | 1      | Reverse roles | none          | Nose-tip         | rejection; visual inspection                            | 0.05    | 100     | -50–500  | Occipito-temporal       | -0.56a         | 150a           | 100–225     |
| Kremláček_2006 [175]            | 9  | Peripheral horizontal sinusoidal grating  | 42.00   | 30.00   | Stimulus  | Visual        | Fixation target                     | 50°/s OD                  | 200      | 600      | 0.06 | 3      | none          | none          | Right earlobe    | correction; PCA                                         | 0.30    | 30      | 0–500    | Occipital               | -2.72a         | 191a           | 145–260     |
| Aneneto_2007 [176]              | 12 | LoVF Peripheral sinusoidal grating        | 4.13    | 4.13    | Stimulus  | Visual        | Fixation number                     | 1.95°/s OD                | 133      | 665      | 0.20 | 1      | none          | none          | Nose-tip         | rejection; excluded trials with eye blinks              | 0.10    | 30      | -50–500  | Posterior               | -3.31          | 198b           | 145–225     |
| Hosak_2008 [177]                | 17 | Peripheral sinusoidal grating             | 42.00   | 30.00   | Stimulus  | Visual        | Fixation target                     | 50°/s OD                  | 200      | 600      | 0.06 | 3      | none          | none          | Right earlobe    | correction; PCA                                         | 0.30    | 30      | 0–1000   | Pz                      | -1.46a         | 180b           | 120–240     |
| Urban_2008 [178]                | 24 | Peripheral horizontal sinusoidal gratings | 40.00   | 30.00   | Stimulus  | Visual        | Central grating motion              | 50°/s ↓ peripheral motion | 200      | 600      | 0.06 |        | none          | none          | Right earlobe    | none; CCD camera                                        | 0.30    | 30      | 0–1000   | Pz                      | -1.41a         | 150b           | 100–200     |
| Langrová_2012 [179]             | 21 | Peripheral horizontal sinusoidal grating  | 37.00   | 28.00   | Black     | Visual        | Central motion target               | 50°/s OD                  | 500      | 1,000    | 0.06 |        | none          | none          | Right earlobe    | rejection; visual inspection                            | 0.30    | 100     |          | Pz                      |                | 180b           | 120–240     |
| Kudlepp_2013 [180]              | 40 | Peripheral vertical sinusoidal gratings   | 27.60   | 20.50   | Stimulus  | Visual        | Target motion                       | 1.6°/s OD                 | 200      | 600      | 0.15 | 1      | none          | none          | Linked-earlobes  | rejection; EOG/EEG threshold exclusion                  | 1.00    | 30      | -100–600 | Parietal                | -0.47          | 167b           | 150–175     |
| Kremláček_2013 [181]            | 12 | Peripheral sinusoidal grating             | 47.00   | 36.00   | Stimulus  | Visual        | Central number changes              | 12.5–25°/s OD             | 100      | 600      | 0.17 |        | Reverse Roles | none          | Right earlobe    | rejection; EOG/EEG threshold exclusion                  | 0.05    | 30      | -99–400  | Centro-parietal         | -0.68          | 172a           | 142–198     |
| Tugan_2016 [182]                | 18 | Peripheral white circular spots           | 2.65    | 2.65    | Black     | Visual        | Fixation cross                      | 42rpm OD                  | 1,400    | 2,800    | 0.14 |        | none          | none          | Average          | rejection; EOG/EEG threshold exclusion                  | 0.50    | 40      | -100–600 | Occipital               | -0.23a         |                | 100–400     |
| Schmitt_2018 [183]              | 8  | Gabor pattern                             | 3.20    |         | Grey      | Visual        | Central or peripheral Gabor pattern | 94° left or right         | 190      | 210      | 0.20 |        | Reverse roles | Equi-probable | Average-mastoids | rejection; excluded trials with blinks or eye movements |         | 50      | -200–900 | Parieto-occipital       | -0.46a         | 160            | 110–190     |
| Rowe_2020 [184]                 | 19 | Peripheral dot array                      | 30.00   | 30.00   | Black     | Visual        | Central letter                      | OD shift                  | 500      | 0        |      | 5      | none          | none          | Average          | rejection; EOG/EEG threshold exclusion                  | 0.50    | 40      | -100–400 | Left posterior          | -0.19a         | 150            | 140–160     |

(Continued)

Table 1. (Continued)

| Study                                        | N  | SOI                                      | W (°VA) | H (°VA) | BG Colour                        | Task Modality | Attention On                          | D-S               | SOI (ms) | ISI (ms) | D%   | Min. S | PC            | AC   | Ref              | Ocular-artifact correction                              | HP (Hz) | Epoch | ROI                    | mean vMMN (µV) | peak vMMN (ms) | Time-window |
|----------------------------------------------|----|------------------------------------------|---------|---------|----------------------------------|---------------|---------------------------------------|-------------------|----------|----------|------|--------|---------------|------|------------------|---------------------------------------------------------|---------|-------|------------------------|----------------|----------------|-------------|
| Schmitt_2021 [185]                           | 12 | Peripheral moving white dots             | 42.00   | 10.90   | Black                            | Visual        | Fixation dot                          | 10° left or right | 350      | 800      | 0.20 |        | Reverse roles | none | Average-mastoids | rejection; excluded trials with blinks or eye movements | 3.00    | 80    | Pz                     | -1.13a         | 135            | 110–160     |
| Inatraglia_2022 [186]                        | 22 | 4x4 blue LEDs on 12x16 LED panel         | 4.20    | 4.20    | Light-emitting diode (LED) panel |               | Count events                          | moved vs. ↑       | 130      | 508      | 0.14 | 4      | none          | none | Average-mastoids | correction; ICA                                         | 0.10    | 40    | Posterior              | -2.11a         | 182a           | 158–198     |
| Duration/omission                            |    |                                          |         |         |                                  |               |                                       |                   |          |          |      |        |               |      |                  |                                                         |         |       |                        |                |                |             |
| Mao_2004 [187]                               | 15 | Central white spot                       | 1.10    | 1.10    |                                  | Visual        | Stimulus duration                     | +300ms            | 300      | 1,100    | 0.25 |        | none          | none | Linked-earlobes  | rejection; excluded trials with EOG artifacts           | 0.05    | 100   | C3                     | -2.40          | 171b           | 156–185     |
| Czigler_2006 [Experiment 1: short ISI] [188] | 10 | LoVF Peripheral matrix of hollow squares | 5.24    | 4.29    | Grey                             | Visual        | Fixation cross and stimulus omissions | -17 ms            | 17       | 92       | 0.10 | 4      | none          | none | Nose-tip         | rejection; EOG/EEG threshold exclusion                  | 0.10    | 30    | Oz                     | -2.56          | 167            | 100–200     |
| Czigler_2006 [Experiment 1: long ISI] [188]  | 10 | LoVF Peripheral matrix of hollow squares | 5.24    | 4.29    | Grey                             | Visual        | Fixation cross and stimulus omissions | -17 ms            | 17       | 162      | 0.10 | 4      | none          | none | Nose-tip         | rejection; EOG/EEG threshold exclusion                  | 0.10    | 30    | Oz                     | -0.22          |                | 100–200     |
| Czigler_2006 [Experiment 2: long ISI] [188]  | 10 | LoVF Peripheral matrix of hollow squares | 5.24    | 4.29    | Grey                             | Visual        | Fixation cross and stimulus omissions | -17 ms            | 17       | 194      | 0.10 | 4      | none          | none | Nose-tip         | rejection; EOG/EEG threshold exclusion                  | 0.10    | 30    | Oz                     | 0.46           |                | 100–200     |
| Czigler_2006 [Experiment 2: short ISI] [188] | 12 | LoVF Peripheral matrix of hollow squares | 5.24    | 4.29    | Grey                             | Visual        | Fixation cross                        | -17 ms            | 17       | 58       | 0.10 | 4      | none          | none | Nose-tip         | rejection; EOG/EEG threshold exclusion                  | 0.10    | 300   | O2                     | -2.83          | 206b           | 186–226     |
| Czigler_2006 [Experiment 2: long ISI] [188]  | 12 | LoVF Peripheral matrix of hollow squares | 5.24    | 4.29    | Grey                             | Visual        | Fixation cross                        | -17 ms            | 17       | 162      | 0.10 | 4      | none          | none | Nose-tip         | rejection; EOG/EEG threshold exclusion                  | 0.10    | 30    | O2                     | -0.21          |                | 188–226     |
| Czigler_2006 [Experiment 2: long ISI] [188]  | 12 | LoVF Peripheral matrix of hollow squares | 5.24    | 4.29    | Grey                             | Visual        | Fixation cross                        | -17 ms            | 17       | 194      | 0.10 | 4      | none          | none | Nose-tip         | rejection; EOG/EEG threshold exclusion                  | 0.10    | 30    | O2                     | 0.16           |                | 188–226     |
| Khodanovich_2010 [Deviant 1] [189]           | 10 | Green light-emitting diodes              | 1.15    | 1.15    |                                  | Visual        | Deviant                               | -50 ms            | 200      | 2,000    | 0.20 |        | Deviant block | none | Average earlobes | rejection; visual inspection                            | 0.16    | 25    | Posterior temporal     | 0.00           |                | 250–350     |
| Khodanovich_2010 [Deviant 2] [189]           | 10 | Green light-emitting diodes              | 1.15    | 1.15    |                                  | Visual        | Deviant                               | -150 ms           | 200      | 2,000    | 0.20 |        | Deviant block | none | Average earlobes | rejection; visual inspection                            | 0.16    | 25    | Posterior temporal     | -1.75a         | 300            | 250–350     |
| Chen_2010 [190]                              | 13 | Central red disc                         | 2.29    | 2.29    | Black                            | Auditory      | Stimulus duration                     | -80 ms            | 200      | 700      | 0.15 |        | Reverse roles | none | Nose-tip         | rejection; EOG threshold exclusion                      | 0.10    | 24    | Parieto-occipital      | -1.27a         | 316b           | 296–336     |
| Qiu_2011 [191]                               | 20 | Peripheral black squares                 | 4.00    | 3.80    |                                  | Visual        | Fixation cross                        | -100 ms           | 150      | 450      | 0.20 |        | Reverse roles | none | Nose-tip         | correction; EOG mathematical correction                 | 0.10    | 100   | Occipital              | -2.74          | 222a           | 200–250     |
| Shi_2013 [73]                                | 12 | Peripheral red rectangles                | 0.10    | 0.30    | White                            | Visual        | Fixation cross                        | 50                | 50       | 550      | 0.10 | 1      | none          | none | Nose-tip         | correction; EOG artifact correction                     | 0.10    | 100   | Occipito-temporal      | -0.65a         | 190a           | 150–250     |
| Wu_2013 [74]                                 | 12 | Peripheral rectangles                    | 3.44    | 1.15    |                                  | Visual        | Central number task                   | +100 ms           | 50       | 550      | 0.10 | 1      | none          | none | Nose-tip         | correction; corrected via EOG regression                | 0.10    | 100   |                        |                | 152            | 150–200     |
| He_2014 [148]                                | 12 | Peripheral green circles                 | 4.20    | 4.20    | White                            | Visual        | Fixation cross                        | +80 ms            | 100      | 400      | 0.09 | 2      | none          | none | Nose-tip         | correction; corrected via EOG regression                | 0.05    | 30    | Left parieto-occipital | 0.86           | 240a           | 220–242     |
| Si_2014 [192]                                | 15 | Peripheral red rectangles                | 4.50    | 4.50    |                                  | Visual        | Fixation cross                        | +50 ms            | 50       | 500      | 0.20 | 2      | none          | none | Nose-tip         | correction; EOG artifact correlation method             | 0.10    | 30    | Occipito-temporal      | -1.10          | 216            | 200–250     |
| Qian_2014 [79]                               | 14 | Peripheral red rectangles                | 0.10    | 0.30    | White                            | Visual        | Fixation cross                        | 50                | 50       | 550      | 0.10 | 1      | none          | none | Nose-tip         | rejection; EOG/EEG threshold exclusion                  | 0.10    | 100   | Occipito-temporal      | -0.69          | 133a           | 150–250     |
| Li_2016a [193]                               | 24 | Peripheral Squares                       | 7.40    | 7.40    | Grey                             | Visual        | Fixation cross                        | +100 ms           | 50       | 500      | 0.10 | 2      | none          | none | Nose-tip         | correction; corrected via EOG regression                | 0.05    | 100   | Fz, Cz, O1, O2, and Oz | -3.95          | 208            | 100–300     |
| Li_2016b [194]                               | 40 | Central Circular Checkerboard (CCC)      | 32.00   | 32.00   | Stimulus                         | Visual        | Deviant                               | Omitted CCC       | 100      | 1,000    | 0.15 | 2      | none          | none | Average-mastoids | correction; EOG artifact correction                     | 0.10    | 30    | Occipito-temporal      | -6.73          | 225a           | 220–270     |

(Continued)

Table 1. (Continued)

| Study                                          | N  | SOI                          | W (°VA) | H (°VA) | BG Colour | Task Modality | Attention On   | D-S          | SOI (ms) | ISI (ms) | D%   | Min. S | PC            | AC      | Ref      | Ocular-artifact correction                                 | HP (Hz) | LP (Hz) | Epoch    | ROI               | mean vMMN (μV) | peak vMMN (ms) | Time-window |
|------------------------------------------------|----|------------------------------|---------|---------|-----------|---------------|----------------|--------------|----------|----------|------|--------|---------------|---------|----------|------------------------------------------------------------|---------|---------|----------|-------------------|----------------|----------------|-------------|
| Yang_2016 [Deviant 1] [195]                    | 21 | Peripheral black squares     | 4.00    | 3.80    |           | Visual        | Fixation cross | +100 ms      | 50       | 600      | 0.20 | 2      | none          | none    | Nose-tip | correction; EOG artifact correction                        | 1.00    | 30      | -100–400 | Occipital         | -1.61          | 218            | 180–260     |
| Yang_2016 [Deviant 2] [195]                    | 21 | Peripheral black squares     | 4.00    | 3.80    |           | Visual        | Fixation cross | -100 ms      | 150      | 600      | 0.20 | 2      | none          | none    | Nose-tip | correction; EOG artifact correction                        | 1.00    | 30      | -100–400 | Occipital         | 0.87           |                | 180–260     |
| Durant_2018 [Decrement deviant 1] [196]        | 20 | Peripheral moving white dots | 0.15    | 0.15    | Grey      | Visual        | Spaceship      | -80 ms       | 200      | 600      | 0.17 | 3      | Reverse roles | none    | Average  | rejection; EOG/EEG threshold exclusion + visual inspection | 0.50    | 30      | -100–400 | Parieto-occipital | 0.00           |                | 220–270     |
| Durant_2018 [Motion decrement deviant 1] [196] | 20 | Peripheral moving white dots | 0.15    | 0.15    | Grey      | Visual        | Spaceship      | -80 ms       | 120      | 600      | 0.17 | 3      | Reverse roles | none    | Average  | rejection; EOG/EEG threshold exclusion + visual inspection | 0.50    | 30      | -100–400 | Parieto-occipital | 0.00           |                | 220–270     |
| Durant_2018 [Motion decrement deviant 2] [196] | 20 | Peripheral moving white dots | 0.15    | 0.15    | Grey      | Visual        | Spaceship      | -80 ms       | 120      | 600      | 0.17 | 3      | Reverse roles | none    | Average  | rejection; EOG/EEG threshold exclusion + visual inspection | 0.50    | 30      | -100–400 | Parieto-occipital | 0.00           |                | 220–270     |
| Durant_2018 [Motion increment deviant 1] [196] | 20 | Peripheral moving white dots | 0.15    | 0.15    | Grey      | Visual        | Spaceship      | +80 ms       | 120      | 600      | 0.17 | 3      | Reverse roles | none    | Average  | rejection; EOG/EEG threshold exclusion + visual inspection | 0.50    | 30      | -100–400 | Parieto-occipital | -0.57          | 231a           | 220–270     |
| Durant_2018 [Motion increment deviant 2] [196] | 20 | Peripheral moving white dots | 0.15    | 0.15    | Grey      | Visual        | Spaceship      | +80 ms       | 120      | 600      | 0.17 | 3      | Reverse roles | none    | Average  | rejection; EOG/EEG threshold exclusion + visual inspection | 0.50    | 30      | -100–400 | Parieto-occipital | -0.17          |                | 220–270     |
| Yang_2019 [197]                                | 15 | Peripheral black Squares     | 3.80    | 4.00    | White     | Visual        | Fixation cross | +100 ms      | 50       | 150      | 0.20 | 2      | Reverse Roles | none    | Nose-tip | correction; EOG artifact correction                        | 1.00    | 30      | -100–400 | Occipital         | -1.92          | 179a           | 150–300     |
| <b>Phase</b>                                   |    |                              |         |         |           |               |                |              |          |          |      |        |               |         |          |                                                            |         |         |          |                   |                |                |             |
| Male_2020 [Experiment 2] [34]                  | 24 | Central Gabor patches        | 3.00    | 3.00    | Grey      | Visual        | Fixation dot   | 1.2π radians | 100      | 400      | 0.13 | 1      | Casadic       | Casadic | Nose-tip | correction; ICA + Eye-tracking                             | 0.10    | 40      | -100–400 | P8                | 0.41           |                | 200–250     |

Note. SOI = stimulus(i) of interest, W = width, H = height, BG = background, D = Deviant, S = Standard, PC = physical control, AC = adaptation control, Ref = Reference, HP = high-pass, LP = low-pass, LoVF = Lower visual field, UVF = Upper visual field, RVF = Right visual field, LVF = Left visual field, D = Opposite Direction

<sup>a</sup> Value was calculated from figures depicting the study or condition within study.

<sup>b</sup> Value represents the midpoint of the time window used to calculate mean amplitude.

<sup>c</sup> Eye movement tracking performed during no EEG recording

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these 160 entries was  $-1.52 \pm 1.2 \mu\text{V}$ . The average peak latency was  $205 \pm 51$  ms. Mean and standard deviation of the number of healthy control participants for all entries was 17 ( $\pm 8$ ), ranging from 6–52.

### 3.2. Linear regression analysis

The linear regression equation which best explained variance in the mean amplitude data,  $R^2 = .134$ ,  $F(3,219) = 11.182$ ,  $p < .001$ , contained:

- whether a control for adaptation was used ( $\beta = .282$ ,  $p < .001$ ), with larger amplitudes where a control was absent,
- whether attention was towards vs. away from the SOI ( $\beta = -.142$ ,  $p = .027$ ), with larger amplitudes where attention was on the SOI, and
- SOI duration ( $\beta = -.139$ ,  $p = .030$ ), with larger amplitudes associated with longer SOI durations,

The regression equation which best explained the variance in peak latency data,  $R^2 = .141$ ,  $F(4,164) = 6.544$ ,  $p < .001$ , contained:

- whether attention was towards vs. away from the SOI ( $\beta = .210$ ,  $p = .005$ ), with later peak latencies where attention was on the SOI,
- ISI ( $\beta = .202$ ,  $p = .008$ ), with later peak latencies associated with longer ISIs,
- the minimum number of standards between deviants ( $\beta = .169$ ,  $p = .024$ ), with later peak latencies associated with increasing number of standards between stimuli, and
- deviant probability, with later peak latencies associated with less frequent deviants ( $\beta = -.170$ ,  $p = .024$ ).

### 3.3. Deviant feature

**Table 2** shows the means and standard deviations for mean amplitude and peak latency and non-binary parameters and for each deviant feature. These are ISI, stimulus duration, deviant probability (as a proportion of 1), and the minimum number of standards (as integers—where the minimum number of standards was not specified, a value of 0 was given).

Although deviant feature did not emerge as a significant predictor of amplitude or latency data, a one-way analysis of mean amplitudes, removing the single entry for phase to allow for Tukey's post-hoc, revealed a significant main effect of deviant feature on mean amplitude,  $F(8,227) = 4.265$ ,  $p < .001$ ,  $\eta^2_p = .135$ , and peak latency,  $F(8,170) = 3.138$ ,  $p = .003$ ,  $\eta^2_p = .135$ .

Overall amplitudes were significantly smaller for orientation compared to luminance ( $p = .001$ ) and spatial frequency ( $p = .011$ ). Luminance also produced significantly larger amplitudes than contrast ( $p = .024$ ), colour ( $p = .006$ ) and shape/size ( $p = .016$ ).

Peak latency was significantly later for spatial frequency deviants than for colour ( $p = .046$ ) and motion ( $p = .002$ ). Peak latency was also significantly later for location deviants than for motion deviants ( $p = .037$ ).

### 3.4. Stimulus duration and ISI

There was a main effect of deviant feature on SOI duration,  $F(8,230) = 3.163$ ,  $p = .002$ ,  $\eta^2_p = .103$ , due to longer SOI duration for motion deviants compared to colour ( $p = .022$ ), shape/size

Table 2. Means (M) and standard deviations ( $\sigma$ ) of mean VMMN amplitude and peak latency for each deviant feature in Table 1.

| Feature                       | Stimulus Duration (ms) | Inter-stimulus-interval (ms) | Deviant (%)     | Minimum N of Standard | Mean Amplitude (M $\pm\sigma$ ) $\mu$ V | Peak Latency (M $\pm\sigma$ ) (ms) |
|-------------------------------|------------------------|------------------------------|-----------------|-----------------------|-----------------------------------------|------------------------------------|
| Orientation                   | 173 $\pm$ 140          | 502 $\pm$ 206                | 0.16 $\pm$ 0.04 | 2.7 $\pm$ 2.39        | -0.75 $\pm$ 0.94                        | 202 $\pm$ 48                       |
| Contrast                      | 86 $\pm$ 32            | 510 $\pm$ 141                | 0.15 $\pm$ 0.03 | 2.33 $\pm$ 1.15       | -0.43 $\pm$ 1.07                        | 160 $\pm$ 11                       |
| Luminance                     | 249 $\pm$ 175          | 488 $\pm$ 194                | 0.17 $\pm$ 0.06 | 3.29 $\pm$ 3.09       | -2.58 $\pm$ 1.86                        | 208 $\pm$ 55                       |
| Spatial Frequency             | 192 $\pm$ 128          | 643 $\pm$ 143                | 0.11 $\pm$ 0.05 | 2.88 $\pm$ 2.03       | -1.69 $\pm$ 1.57                        | 238 $\pm$ 62                       |
| Colour                        | 141 $\pm$ 172          | 751 $\pm$ 454                | 0.16 $\pm$ 0.07 | 1.71 $\pm$ 1.15       | -0.84 $\pm$ 0.94                        | 194 $\pm$ 46                       |
| Shape or Size                 | 119 $\pm$ 101          | 703 $\pm$ 372                | 0.14 $\pm$ 0.04 | 1.82 $\pm$ 1.07       | -0.89 $\pm$ 0.83                        | 205 $\pm$ 63                       |
| Location                      | 175 $\pm$ 40           | 1081 $\pm$ 470               | 0.17 $\pm$ 0.1  | 2.88 $\pm$ 0.99       | -1.69 $\pm$ 0.99                        | 234 $\pm$ 47                       |
| Motion Direction              | 300 $\pm$ 330          | 732 $\pm$ 616                | 0.15 $\pm$ 0.06 | 2.22 $\pm$ 1.56       | -1.34 $\pm$ 0.99                        | 168 $\pm$ 18                       |
| Stimulus Duration or Omission | 97 $\pm$ 76            | 597 $\pm$ 486                | 0.15 $\pm$ 0.05 | 2.67 $\pm$ 1.06       | -1.16 $\pm$ 1.71                        | 211 $\pm$ 48                       |
| Phase                         | 100 $\pm$ 0            | 400 $\pm$ 0                  | 0.13 $\pm$ 0.00 | 1.00 $\pm$ 0.00       | 0.41 $\pm$ 0.00                         |                                    |
| Total                         | 165 $\pm$ 157          | 633 $\pm$ 378                | 0.15 $\pm$ 0.06 | 2.47 $\pm$ 1.85       | -1.07 $\pm$ 1.24                        | 206 $\pm$ 53                       |

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( $p = .010$ ), and duration deviants ( $p = .002$ ). SOI duration emerged as a significant predictor in regression analysis of mean amplitude data only, with larger amplitudes associated with longer SOI duration.

There was an effect on ISI,  $F(8,234) = 4.526$ ,  $p < .001$ ,  $\eta^2_p = .139$ , due to longer ISIs for location deviants compared with orientation ( $p < .001$ ), contrast ( $p = .048$ ), luminance ( $p = .012$ ), spatial frequency ( $p = .019$ ), and duration/omission deviants ( $p = .006$ ). The colour vs. orientation difference in ISIs was also significant ( $p = .020$ ). ISI emerged as a significant predictor in regression analysis of latency data only, with later vMMN peak latencies associated with longer ISIs.

### 3.5. Oddball deviant probability and minimum number of standards preceding a deviant

Only 5% ( $n = 11$ ) of Table 1 entries did not declare a deviant probability of 20% or less. Deviant probabilities did not differ across deviant features. Over half of the entries (63%,  $n = 150$ ) stipulated a minimum number of standards between deviants and 56% ( $n = 104$ ) stipulated at least two standards must separate deviants. There was no effect of deviant feature on the number of standards separating deviants. Both deviant probability and minimum number of standards emerged as significant predictors in regression analysis of latency data, with later peak latencies associated with greater number of standards separating deviants and less frequent deviants.

### 3.6. Isolating and manipulating deviant features, equating physicality of stimuli, and adaptation

Table 1 shows 59% compared physically identical stimuli ( $n = 141$ ) to ensure that differences in processing did not reflect differences in the physical properties of a stimulus. Of the available methods used to parse differences in physical properties of stimulus in Table 1, only the equiprobable and cascading control accounts for differences in the ERPs due to adaptation. Only 23% ( $n = 54$ ) included a control for adaptation (38% of those that used a physical control). Regression analysis shows that whether an adaptation control is used is the strongest predictor of mean amplitude, with larger amplitudes where a control was absent than when a control for adaptation was present.

### 3.7. Attention and fixation

Of all [Table 1](#) entries, 79% ( $n = 189$ ) directed attention away from the stimulus of interest. It appears that directing attention away from the stimulus of interest is common practice in feature-deviance vMMN research. Of all [Table 1](#) entries, 66% ( $n = 158$ ) used a fixation target, dot, square, cross, or tracking task and 60% ( $n = 142$ ) directed attention away from the stimulus of interest and while using fixation stimulus. Attention emerged as a significant predictor of mean amplitude and peak latency, with larger and later vMMNs produced where attention was on vs. away from the relevant stimulus.

### 3.8. Reference and filter frequency

Of the 234 entries with reference details, 54% ( $n = 126$ ) used a nose-tip or non-cephalic reference, 10% ( $n = 23$ ) used a unipolar reference, 20% ( $n = 46$ ) used the average, and 17% ( $n = 39$ ) used linked or averaged earlobes/ mastoids/electrodes, illustrating a clear preference for the nose-tip/non-cephalic reference in vMMN research. The general approach to selecting a low-pass (LP) filter frequency in vMMN research is relatively consistent. Of those who reported a LP filter ( $n = 231$ ), 48% ( $n = 112$ ) used a 30 Hz cut-off. High-pass (HP) filter cut-off frequencies are more variable, ranging from 0.03–1.5 Hz.

### 3.9. Visual MMN region of interest (ROI) or electrode

Of the 233 entries with ROI or electrode details, 99% ( $n = 228$ ) reported their results from parietal (P), occipital (O), and/or occipito-temporal ROIs or electrodes. Of those that specified a left or right ROI or electrode ( $n = 82$ ), 78% ( $n = 64$ ) indicated a right hemisphere ROI or electrode—22% ( $n = 18$ ) reported a left hemisphere ROI or electrode.

### 3.10. Magnitude of deviance

**3.10.1. Orientation.** Regression analysis including those significant predictors of mean amplitude as well as standardized magnitude of deviance saw magnitude of deviance replace SOI duration as a significant predictor of mean amplitude. The regression equation which best explained the variance,  $R^2 = .297$ ,  $F(3,73) = 9.851$ ,  $p < .001$ , contained:

- whether a control for adaptation was used ( $\beta = .214$ ,  $p = .080$ ), with larger amplitudes where a control was absent,
- whether attention was towards vs. away from the SOI ( $\beta = -.304$ ,  $p = .005$ ), with larger amplitudes where attention was on the SOI, and
- magnitude of deviance ( $\beta = -.330$ ,  $p = .009$ ), with larger amplitudes associated with larger magnitudes of deviance.

Including all 10 predictors (not deviant feature), the regression equation that best explained the variance in amplitude,  $R^2 = .333$ ,  $F(4,72) = 8.273$ ,  $p < .001$ , contained:

- whether a control for adaptation was used ( $\beta = .310$ ,  $p = .011$ ), with larger amplitudes where a control was absent,
- ISI ( $\beta = .297$ ,  $p = .006$ ), with larger amplitudes associated with shorter ISIs,
- magnitude of deviance ( $\beta = -.291$ ,  $p = .016$ ), with larger amplitudes associated with larger magnitudes of deviance, and

whether there was a fixation task or not ( $\beta = .249$ ,  $p = .019$ ), with larger amplitudes where there was no fixation.

The variation explained by (and the trend in) magnitude of deviance was significant (and in the same direction) in both results for orientation entries. Regression analyses did not provide support for an effect of magnitude of deviance on peak latency for orientation deviants.

**3.10.2. Spatial frequency.** No regression analyses produced a regression equation in which magnitude of deviance was a significant predictor of either mean amplitude or peak latency.

## 4. Discussion

This review comprises a tabular summary of the vMMN feature deviance research. Meta-analyses suggest that various parameters of experimental design can have (intended or unintended) effects on the resulting vMMN.

Of the 10 predictors explored overall, whether a control for adaptation was used, whether attention was towards vs. away from the relevant stimulus, and relevant stimulus duration emerged as significant predictors of vMMN mean amplitude while whether attention was towards vs. away from the relevant stimulus, ISI, deviant probability, and the number of standards separating deviants emerged as significant predictors of vMMN peak latency.

Magnitude of deviance also emerged as a significant predictor of mean amplitude for orientation entries—the most investigated feature of visual input in vMMN research. And, when including all 10 predictors in a regression analysis of the data for orientation entries, fixation (towards vs. away from the relevant stimulus) replaced attention as a significant predictor of mean amplitude.

In the discussion that follows, I consider parameters that emerged as a significant determinant of either mean amplitude or peak latency as well as parameters that did not but have been reported for influencing the vMMN. All results are exploratory and should be interpreted in the context of studies that examine the effect of varying any of the following parameters in the same participants given the limitations associated with revealing effects across participants as opposed to within the same participants.

### 4.1. Deviant feature

Relatively few have examined various deviants within the same participants [69, 73, 79, 142, 148]. In one study, Qian et al. [79] manipulated five features of visual input. They reported the largest vMMN for orientation deviants compared to colour, duration, shape, and size deviants. Sulykos and Czigler [69] also reported a larger vMMN for orientation deviants than for spatial-frequency deviants. However, the current results suggest that orientation deviants ( $-0.75 \pm 0.94 \mu\text{V}$ ) produce smaller mean amplitudes than spatial frequency deviants ( $-1.69 \pm 1.57 \mu\text{V}$ ). Location deviants ( $-1.69 \pm 0.99 \mu\text{V}$ ) produced larger amplitudes than colour ( $-0.84 \pm 0.94 \mu\text{V}$ ) and shape/size ( $-0.89 \pm 0.83 \mu\text{V}$ ). This is in line with Grimm et al. [142], however, regression analysis did not provide any evidence that the deviant feature predicted vMMN mean amplitude (or peak latency). One possibility is that the remaining predictors primarily influence the amplitude differences, and once this is accounted for, the variability between feature deviants may be less than expected.

Although the current review and meta-analysis goes some way toward addressing this possibility by comparing results across deviant features, continued comparisons of deviant features in the same participants seems prudent for delineating whether different deviants evoke different sized vMMNs as in Grimm et al. [142] and for confirming the reasons for this, such as perceived difference, as in Takács et al. [72].

## 4.2. ISI and stimulus duration

It is generally accepted that shorter ISIs produce larger vMMNs than longer ISIs [55, 62, 150]. Illustrating this effect within the same participants, Fu et al. [62] found that a 100 ms ISI evoked a larger vMMN than a 400 ms ISI. Astikainen et al. [55] proposed that the short duration of the sensory memory trace—less than 1000 ms according to behavioural research [198–200]—was responsible for the absence of a vMMN in their 1000 ms ISI condition [55]. This view suggests that the monotonic relationship between ISI and vMMN is explained by memory trace decay.

Another possibility is that ISI duration determines confidence in the encoded regularity and, by corollary, regularity-based predictions. Daikhin and Ahissar [201] found that jittering the frequency values of standard tones—within a 0.5% range of 1000 Hz—yielded smaller MMNs than if all standards had the same frequency (i.e., 1000 Hz). They argued that confidence in the predictive model was lower in the jittered condition than in the non-jittered condition. Therefore, the strength of prediction determines, at least to some extent, the size of prediction error [4]. Perhaps ISI similarly determines confidence in the predictive model. Consider that if confidence is high because ISI is short, then perhaps prediction error is larger, yielding larger vMMNs, than when ISI is long. The current regression analyses indicate that shorter ISIs are associated with shorter vMMN peak latencies for deviants overall and that shorter ISIs are associated with larger vMMN amplitudes for orientation deviants.

This may also explain the observed association between stimulus duration and vMMN amplitudes in the current review, where longer stimulus durations enhance confidence in the predictive model, thereby generating larger vMMNs. However, as noted elsewhere [34], longer stimulus durations can pose challenges in EEG research because the onset of a stimulus can trigger eye movements toward it. According to Westheimer [202], saccades can begin 120 ms after stimulus onset and reach peak acceleration at 160 ms, falling within the vMMN time-window. Therefore, a shorter stimulus duration (e.g.,  $\leq 100$  ms) may be better for avoiding confounds associated with eye movement and stimulus durations as short as 14 ms [140] and 17 ms [203] have been used to successfully evoke a vMMN for feature deviants.

Although others have manipulated stimulus duration as the deviant feature, there are no known studies that have manipulated stimulus duration to delineate its effect on the vMMN to an unrelated (non-duration) feature deviant. The current regression analysis indicates that longer stimulus presentations predict larger vMMNs, providing compelling rationale for further investigation into this phenomenon. The association not only highlights the importance of stimulus duration in understanding vMMN amplitudes but also underscores the potential for refining predictive models in EEG research.

## 4.3. Oddball deviant probability and minimum number of standards separating deviants

A deviant must be infrequent to constitute an irregularity. Standards establish regularity, making it important to separate deviants by at least two standards; otherwise, the deviant may not constitute an irregularity. Consider, however, that measures of deviance reflect increased deviant processing as well as reduced standard stimulus processing and that repetition suppression tends to increase with the number of standards preceding the deviant [106]. As a result, greater repetition suppression can create the appearance of a stronger response to deviance [96, 106], emphasizing the need to consider the number of standards that separate deviants.

Most studies in the current review reported a deviant probability of 20% or less. This may relate to the well-established association between higher deviant probabilities and smaller MMNs [204–207]. In the visual domain, Stefanics et al. [208] found that deviants with a lower

(10%) probability evoked larger vMMNs than deviants with a higher (30%) probability. The authors also observed that conditions with 30% deviants produced a significant difference at 134–160 ms (earlier) whereas conditions with 10% deviants produced a significant difference at 232–254 ms (later). The current results further demonstrate that a higher deviant probability predicts earlier vMMN peak latencies, supporting the findings of Stefanics et al. [208]. Relatedly, later peak latencies were associated with a greater number of standards between deviants.

One explanation regards greater decay in the memory trace of the standard (e.g., [206, 207]). That is, as the memory trace of the standard stimulus fades over time, the brain's ability to detect deviations from that standard diminishes. In conditions with higher percentages of deviants (like 30%), the brain may rely more on immediate comparisons rather than on a decaying memory of the standard. Alternatively, reasoning reflects enhanced memory trace for the deviant [204, 205].

Alternatively, the number of standards between deviants might influence the vMMN by influencing the ratio of successful: unsuccessful vMMN trials. If only some deviant trials generate a vMMN (due to the presence or absence of two or more standards preceding the deviant on some trials but not others), the resulting vMMN amplitude will be smaller compared to situations where all deviant trials elicit the vMMN, due to the averaging process. Horváth et al. [209] discussed this phenomenon in the context of magnitudes of deviance near the discrimination threshold. They proposed that, as the audible discrimination of irregular tones approaches the discrimination threshold, the ratio of trials that fail to evoke the MMN increases, while the ratio of deviant trials that evoke the MMN remains constant when the deviant is easily distinguishable. Consequently, averaging the trials creates the appearance of a magnitude of deviance effect limited to differences near the discriminable threshold. Similarly, if some trials evoke the vMMN while others do not, the overall vMMN amplitude will be smaller compared to situations where all deviant trials consistently elicit the vMMN.

Another possibility is that the neural correlate of a violation will be more pronounced when the model of regularity is more precise [210] and the model is more precise when there are more standards separating deviants. Several factors can influence model precision, including the stability or volatility of the environment [211–214] which is indeed determined by the similarity among standards. Still, the reason for the impact of volatility remains unclear. However, one possibility is that repetition suppression is greater in less volatile sequences.

Ultimately, there are various mechanisms by which the number of standards separating deviants may affect the vMMN, making it important to consider. Given the strong theoretical basis for ensuring a minimum number of standards separate deviants together with findings that repetition suppression increases as the number of standards preceding the deviant increases, affecting vMMN size, a minimum number of two standards is recommended.

#### 4.4. Isolating and manipulating deviant features, equating physicality of stimuli, and adaptation

Whether a control for adaptation-related differences was absent or present emerged as a significant predictor of mean amplitude, illustrating the importance of controlling for adaptation-related differences. Logically, the combined adaptation-related and deviance-related differences should yield a larger DRN than a genuine vMMN that is free from adaptation. Meanwhile, whether a physical control was present did not emerge as a significant predictor for latency or amplitude data. This may reflect the variability in true isolation of physical features of the visual stimulus due to use of comparatively complex visual stimuli.

Consider that a visual stimulus is composed of a unique combination of visual features, the presence of these features, along with their interaction, determines which neurons respond.

Altering even a single feature changes the corresponding ERP. Despite this, many visual stimuli in vMMN research lack the simplicity of manipulation of a single property of visual input without influencing others. To illustrate, in a study by Mazza et al. [215], ERPs were compared for red triangle stimuli and green disc stimuli. Although their roles as deviants and standards were reversed, stimuli not only varied in colour, but also in all features that distinguish their shapes (e.g., contour orientation, stimulated retinal areas, spatial frequency). Therefore, any observed differences in their ERPs could arise from one, multiple, or all these variations.

Conversely, a key advantage of a Gabor patch lies in the separability of their stimulus features. Specifically, modifying a single aspect of a Gabor patch, such as its orientation, has no impact on other features like spatial frequency or luminance. Potentially, the true isolation of low-level features of the visual stimulus may explain why changes in Gabor patches yield much smaller vMMNs than similar changes in non-Gabor patch stimuli ( $t(225) = -4.167, p < .001$ ). Another advantage of Gabor patch stimuli is that they are physiologically plausible visual stimuli due to their profile resembling that of a receptive field in the visual cortex's simple cells [216–218]. They are also highly favoured among visual psychophysicists [216], facilitating the seamless translation of research findings between visual psychophysics and visual neuroscience.

Notably, larger deviant-minus-standard differences often peak earlier due to the N1 difference. Some researchers classify early (i.e., 150–200 ms) and late (200–250 ms) time-windows to distinguish between N1 adaptation (early) vs. deviance related differences (late) [79, 87, 91, 93, 99, 101]. This may account for some of the early peak latencies reported where there is no control for adaptation (e.g., 130 ms in [69] and 134 ms in [72]). However, this approach cannot discount the possibility that adaptation-related differences are still present in the later time periods and may explain why there was no supporting evidence for an effect of adaptation on peak latency.

#### 4.5. Attention, fixation, and ocular artifacts

There are several compelling theoretical and practical reasons for diverting attention away from the stimulus of interest in vMMN research. Firstly, when researchers initially explored the existence of a visual counterpart to the MMN, a crucial prerequisite was that it must occur without attention [21]. Focusing attention on the stimulus of interest hinders the ability to draw definitive conclusions about whether the vMMN genuinely mirrors the MMN [1, 2].

Secondly, directing attention away from the stimulus of interest is essential because attention can influence the vMMN [109, 180, 190]. For example, Kuldkepp et al. [180] found that directing attention away from the stimulus of interest is necessary to evoke both early and late subcomponents of the vMMN. However, there is also evidence that attention toward the stimulus of interest can enhance a vMMN response to a deviant that might not otherwise elicit a vMMN (e.g., [219]).

One potential explanation for the latter phenomenon is that the process of detecting deviance in vision differs from that in audition, such that some level of attention or an additional cognitive resource is required to detect changes in visual input. Another possibility is that attention could influence vMMN amplitudes by enhancing ERP components within the vMMN time window in which case, alterations in negativity might reflect shifts in attention rather than the direct detection of deviance (e.g., N2b, [220]).

While many of the reviewed studies used a central fixation stimulus, Table 1 shows various other means have been employed for directing attention away from the stimulus of interest. For example, Sulykos and Czigler [69] designed the Spaceship task to control participants' attention. Participants navigated a spaceship through a canyon—a rectangular object vertically

and horizontally segmented giving the impression of depth and a horizon—while avoiding/catching colour-determined targets. Targets were other spaceships [83] or coloured doors [69]. Although this task ensures attention is effectively diverted away from the relevant stimulus, it does not ensure consistent eye gaze position because the eyes must move to recenter the object being tracked. In visual experiments, eye movements have the capacity to convert simple orientation changes into more complex visual alterations. Therefore, fixation tasks are ideal for ensuring that attention is diverted away from the stimulus of interest *and* ensuring that the visual system is exposed to the intended change in visual input, mitigating risk that other changes contribute to the observed ERP differences.

The fixation method was also one of the primary methods introduced for reducing ocular-artifacts [221]. This was typically used in combination with the rejection technique—discarding epochs containing voltage fluctuations in EOG or both EEG/EOG channels that are larger than a preset value is discarded [221]. Historically, the rejection method was most common [222]. Criticisms of the method include considerable loss of data and arbitrary threshold selection, with EOG artifacts below threshold still contributing to ERPs. In response to these criticisms, methods of correction rather than rejection, including regression analysis [221, 223], PCA [224], and ICA [225]. While the rejection technique is still widely used, the ICA approach has become increasingly popular in recent years (e.g., [93, 105, 133]). Of 68 studies since 2014 in Table 1, 43% (n = 29) used corrections to deal with ocular artifacts compared with the 56% that used rejection technique (n = 38). For a review of methods evolved to correct EEG artifacts see [226].

Despite the importance of ensuring that participants' eyes remain open and fixated, the use of eye-tracking in the field is sparse, with only four Table 1 studies having implemented some measure of gaze position [26, 34, 100, 178]. When a stimulus does not occupy a uniform area of the visual field on every iteration, gaze position is more variable, and this has the potential to change a simple feature deviant into a more complex deviant. I previously reported greater gaze variability in an experimental condition in which a central grey bar appeared on a black background compared with an experimental condition in which a central Gabor patch appeared on a grey background [34]. Although the bar condition was a replication of Kimura et al. [66], we did not replicate the previously reported vMMN. One possible explanation is the additional emphasis on fixation in the replication condition via (i) use of eye-tracking, and (ii) additional intermixed conditions that required fixation for task completion. While gaze position was most variable in the replication condition, we believe it would have been even more variable without the added conditions and eye tracking. This variability can affect the perception of a simple feature deviant, making it more complex. Supporting this idea, regression analysis revealed that mean amplitudes were larger when fixation was not maintained than when it was.

In summary, the current results suggest that attention towards the stimulus of interest evokes larger and later vMMNs. Together with the strong theoretical and practical reasons for controlling fixation, the current review underscores the importance of considering attention and fixation in vMMN research.

#### 4.6. Magnitude of deviance

Few have examined the relationship between magnitude of deviance and the vMMN, despite a potential to gain further insight into prediction error. Consider, for example, that if the sole purpose of the prediction error is to update the predictive model, then a monotonic relationship between the magnitude of deviance and the vMMN, in which larger magnitudes of deviance evoke larger vMMNs, is unnecessary per Horváth et al. [209]. Alternatively, if larger

magnitudes of deviance produce larger prediction errors, then perhaps this is because larger vMMNs also predict later processes, such as the re-orienting of attention. Evidence of a monotonic relationship between amplitudes of the MMN and P3a—a known neural correlate of attention capture [157, 227]—supports the view that the size of the prediction error predicts attention switch [47, 228]. Another possibility is that the size of prediction error represents the extent of violation and this determines whether the model is abandoned versus updated [219].

Still, it remains unclear whether a monotonic relationship exists between magnitude of deviance and the vMMN. Several factors contribute to this ambiguity. Firstly, assertions about the connection between deviance magnitude and prediction error size largely rely on findings from MMN research, where there is a tendency for larger deviance magnitudes to elicit larger and earlier MMNs [16, 201, 228–235]). That said, certain experimental manipulations, such as attention allocation, have been found to affect the vMMN and MMN differently [26]. Given this, it is plausible that other experimental manipulations, like magnitude of deviance, have distinct effects on the vMMN and MMN.

Secondly, the existing body of research on the relationship between magnitude of deviance and the vMMN is both limited and marked by contradictions [57, 58, 61, 68, 72, 236]. For example, Czigler and Sulykos [68] found no discernible effect when using orientation deviants whereas Takács et al. [72] observed an effect on vMMN amplitude but not latency. Meanwhile, Maekawa et al. [57] reported an effect on vMMN latency but not amplitude. Maekawa et al. [57] manipulated spatial frequency via the number of vanes in a windmill pattern. Moreover, Clifford et al. [27] and Mo et al. [145] found that between-category colour deviants elicited larger vMMNs than within-category colour deviants, even though both deviants were equally distant from the standard on the colour spectrum. This suggests that the effect may be influenced more by an abstract property of the input (i.e., the category) rather than the specific feature itself (i.e., the colour). Supporting this interpretation, Thierry et al. [143] and Athanasopoulos et al. [237] demonstrated that learned linguistic associations—higher order top-down effects—influenced the perceived magnitude of deviance.

Meanwhile, Czigler et al. [58] found that small colour deviants (red vs. pink) did not evoke a vMMN whereas large colour deviants (red vs. green) did. Although this could represent a magnitude of deviance effect, it might also imply the need for a higher deviance threshold for colour deviants. The concept of a threshold has been considered elsewhere [235] and is supported by a study in which Takács et al. [72] increased their orientation difference from 50° to 90° after finding that the 90° difference more consistently evoked the vMMN than the 50° deviance. Following their first experiment, the authors conducted a psychophysical assessment on the threshold for orientation change detection with stimuli similar to those used the oddball paradigm. Taken together, the authors concluded that unlike the MMN in the auditory modality, in the visual modality, significantly larger differences are needed to evoke the vMMN. The threshold required for any feature deviant is not yet known and there is yet to be a study in which thresholds of deviance detection revealed by the vMMN are explored across deviant features.

The third and arguably the most challenging hurdle in deciphering the relationship between the magnitude of deviance and the (v)MMN lies in the fact that a significant portion of the research examining this relationship did not incorporate a control for adaptation. This poses a particular challenge because larger disparities between adapted and unadapted stimuli result in more substantial ERP differences, creating an appearance of a deviance magnitude effect (e.g., [201]). Recently, researchers who incorporated controls for adaptation while manipulating magnitude of deviance have not found the vMMN, let alone an effect of magnitude of deviance [106]. For these reasons, drawing conclusions about the association between magnitude of deviance and the vMMN based on the current literature remains challenging.

To help remedy this, I explored the magnitude of deviance effect in the tabulated orientation and spatial frequency entries separately. Regression analyses indicated larger amplitudes for larger magnitudes of deviance, indicative of a monotonic relationship, perhaps for the purpose of determining processes that follow such as attention or model updating. However, this finding relates to orientation only and there was no evidence of an effect of magnitude of deviance on vMMN amplitude or peak latency for spatial frequency deviants [57]. This may reflect the fewer spatial frequency entries. Alternatively, it may indicate that the effects of magnitude of deviance differ across deviants, as suggested by the aforementioned studies. Further research on the effect of magnitude of deviance under conditions where a genuine vMMN is achieved is needed to reach a conclusive understanding of the relationship between deviance magnitude and the vMMN.

#### 4.7. EEG processing parameters

Although there are various processing parameters to consider, I focus on reference and filter frequency because both are known to have downstream effects on ERP component measures. Specifically, chosen reference can affect a component's peak (e.g., amplitude), time of maximum negativity (e.g., peak latency), where it is largest (e.g., electrode or ROI), and even its polarity [238, 239]. A unipolar reference (e.g., the left or right earlobe or mastoid) can bias data toward one hemisphere by producing enlarged ERP amplitudes opposite the recording site [240]. In one Table 1 study, Tales et al. [122] described a possible disadvantage in using references like Fz in that this is sometimes accompanied by frontal positivity in both the visual and auditory modalities and this would appear as additional negativity, thereby exaggerating posterior components. Re-referencing the data to the average of left and right reference electrodes (e.g., earlobes or mastoids) can help to avoid this [241]. This has been called linked-earlobes or linked-mastoids. However, linked-earlobes or linked-mastoids can also mean forcing the two sites to have the same voltage and this process does not alleviate the problem. The version of re-referencing is not always clear [240]. Although vision researchers considered the nose-tip electrically neutral and optimal in EEG research [240] re-referencing to the average is now considered optimal, especially for a high-density recording montage (i.e., at least 32 electrodes) [239–242].

Temporal filtering is a process in which one attenuates signals (e.g., electrical noise or activity) oscillating at a given rate. Frequency cut-off values in Hertz (Hz) determine the range of frequencies to preserve. For example, power mains in Australia produce regularly oscillating electrical activity at approximately 50 times per second (50 Hz). A low-pass filter cut-off value of below 50 Hz (e.g., 40 Hz) will attenuate the effect of all signals at frequencies above this value. Ultimately, the goal of filtering is to increase the signal-to-noise ratio (SNR) in the electrophysiological data and is therefore common practice in EEG research [243]. Cut-off frequencies that are  $>0.1$  Hz (e.g., 1 Hz) can produce artifactual early negativities as early as 100 ms after onset [243–246]. This could be problematic where DRN or vMMN calculations include all ERP values between before 150 ms (e.g., [26, 27, 80, 86–88, 92, 102, 107, 108, 115, 120, 128, 135, 140, 174, 178, 182, 188, 193]).

#### 4.8. Replicability of vMMN for feature deviants and its implications for meta-analysis

The current meta-analysis aims to uncover overarching trends and reveal patterns across studies. However, it also illuminates inconsistent effects and contextual factors underlying varying results. For example, Kimura et al. [66] reported a vMMN more than twice the size of the vMMN reported by Astikainen et al. [55] ( $-1.60$   $\mu$ V vs.  $-0.69$   $\mu$ V). Both studies used single

grey bar stimuli on a black background, 36° orientation deviants, at least two standards between deviants, 100 ms stimulus duration, 400 ms ISI, and the equiprobable control. Similarly, despite using similar windmill-like patterns, Maekawa et al. [57] reported a vMMN at 185 ms, whereas File et al. [86] reported a vMMN at least 70 ms later. This may be related to deviance detection, such as the magnitude of deviance (i.e., the difference in the number of windmill-panes in File et al. [86] was six compared to 18 in Maekawa et al. [57]), or differences in processes outside of deviance detection, such as attention or adaptation (i.e., File et al. [86] used the equiprobable control whereas Maekawa et al. [57] compared identical stimuli as deviants and standards—reverse roles condition).

Moreover, there are an increasing number of studies emerging that illustrate the absence of a vMMN to changes in low-level features of visual input, like contrast, orientation, and spatial frequency (red values in Table 1). These are categorically low-level features because they are integral dimensions for describing the visual appearance of images and are processed in the visual cortex (V1) or earlier [34]. While the absence of vMMN is easier to reconcile in studies exploring rarely tested features, such as contrast, it poses a more challenging issue for frequently tested features like orientation and spatial frequency. Potentially, the stimulus used is implicated. For example, Sulykos et al. [71] did not observe the vMMN when using Gabor patches on a black background. The authors attributed this to a failure in reactivating the memory trace of a previous standard. However, others using centrally presented Gabor patches on a grey background also reported no vMMN for orientation changes of 36° [34] or 60° [106]. File et al. [86] also did not observe orientation vMMN when using peripherally presented line textures. Interestingly, however, in the same study, when using comparatively more complex stimuli than either Gabors or line textures (i.e., windmill patterns), File et al. [86] found that increases (not decreases) in spatial frequency (i.e., more windmill panes) evoked the vMMN whereas decreases in spatial frequency (i.e., fewer windmill panes) did not. They proposed that the former represented a more complex change requiring prediction error whereas the latter did not. However, additional changes in stimuli, such as added orientation information for increases but not decreases in spatial frequency, may contribute to the observed effects. This raises uncertainty about the capability of low-level feature such deviants to evoke the vMMN, let alone reveal the true effects of design parameters. If truly isolated changes to low-level features fail to elicit the vMMN, investigating how experimental design parameters impact the vMMN may require testing with comparatively more complex stimuli, such as windmill panes. The paradox arises, as controls for fixation, adaptation, and physicality become even more critical when using complex stimuli, they are less frequently implemented. The recommendations for parameters outlined in this review may potentially aid in designing paradigms to delineate these effects with complex stimuli within participants.

#### 4.9. Limitations

Although the current review has many strengths, there are limitations to consider. For one, although there are many experimental parameters/variables, the number of variables analysed was limited to those that were comparable across studies while ensuring at least 10 distinct studies per predictor [247]. For example, although useful for showing the different sizes of stimuli used in vMMN research, stimulus size was not entered into regression analyses given that the precise area of the monitor occupied by the stimulus is not so easily quantified by any stimulus that is not simply a square, rectangle, or circle.

Additionally, despite the importance of adequate sample sizes, the studies reviewed had an average of only 17 participants, with some conditions including as few as six. Table 1 shows that small, potentially underpowered samples remain common, posing risks to conclusions

across much of the neuroscience literature. Small samples are associated with low replication rates, exaggerated effect estimates when findings are statistically significant, and poor predictive power [248]. These may contribute to the contradictory results observed in some entries in Table 1, underscoring the need for larger samples in the field.

Standardization of variables is another consideration. The minimum number of standards separating deviants (as integers) was coded as 0 for entries in which a minimum number of standards was not specified. Consequently, if this is not accurate (e.g., the authors did indeed ensure that at least 1 or more standard separated all deviants), the result may not be a true reflection of the relationship. Lastly, due to a sparse number of reported effect sizes in this area of work (details in supplementary materials S1 Text), the traditional means of illustrating bias which rely on effect sizes (or the means of calculating them via measures of variance) are difficult. Instead, a qualitative approach is used to summarize instances where values or pieces of information were estimated so as to not discount the entry entirely. Although the qualitative approach was recently used by Liu et al. [249], it does not facilitate an easily quantifiable assessment of bias in the field. To promote progress in the field, it would be beneficial to report effect sizes across all vMMN conditions in future studies.

## 5. Summary

I examined the existing literature on feature deviants to reveal the impact of experimental design parameters on the only known neural correlate of prediction error in the visual system—the vMMN. I explored the implications associated with these parameters either having or lacking an effect within the framework of predictive coding theory and reflected on the parameters worth considering, emphasizing practical and theoretical basis for certain parameter choices. I highlight existing gaps in knowledge concerning the effects of many design parameters, possibly due to inconsistencies in the literature and challenges in replicating the vMMN response to unanticipated changes in low-level features of visual input. As is often the case, the results encourage more questions than answers. However, this review may help guide those intending to pursue such critical questions, including does the vMMN differ for different feature deviants or does magnitude of deviance affect the vMMN similarly for all feature deviants? By demonstrating that the vMMN is affected by various parameters of experimental design, this review emphasizes the importance of a well-controlled and considered experimental design, for which the current review can also assist.

## Supporting information

### S1 Text. Systematic review.

(DOCX)

### S2 Text. Bias estimates.

(DOCX)

**S3 Text. Assessing certainty level of body of evidence.** Contains **S1 Table:** GRADE assessment of risk of bias, unexplained heterogeneity or inconsistency of results, indirectness of evidence, indirectness of evidence, imprecision of results, probability of publication bias.

(DOCX)

**S1 Fig. PRISMA flow diagram.** Illustrates the database searches, abstract screenings, and full-text retrievals conducted in the systematic review.

(PDF)

**S2 Fig. Summary of risk of bias.** Red: High risk \* Indicates that the value/parameter/condition is absent from the study design; Yellow: Unclear risk \* Indicates that the value was estimated rather than explicitly stated in the text; Green: Low risk \* Indicates that these parameters were clearly stated in the studies.  
(PDF)

**S1 Data. Systematic review records.** Original 948 records returned with exclusion/inclusion metrics.  
(PDF)

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