Task Dependency of Binocular Disparity in Temporal Eye Movement Analysis: Binocular Coordination Post-Print

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Abstract

To maintain the integrity and unity of subjective visual perception, precise coordination and integration between the two eyes are required during information collection. However, existing domestic literature has predominantly conducted "monocular vision" research based on Hering' s law. When children with autism and control group children viewed videos of different emotions, an eye tracker recorded their eye movements with high precision. After different types of noise in the high-precision data were selectively filtered out, the changes in binocular disparity over the time series were clearly revealed, forming a temporal eye movement analysis pattern. The analysis results indicated: 1) Binocular disparity varied significantly across different emotional faces, supporting the Helmholtz hypothesis and emphasizing coordination between the two eyes; simultaneously, 2) the binocular disparity of the two groups of subjects differed significantly across all emotional faces, further revealing the perceptual specificity in children with autism.

Full Text

Task Relevance of Binocular Disparity in Temporal Eye Movement Analysis: Binocular Coordination

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Abstract

To maintain the integrity and singleness of subjective visual perception, precise coordination and integration of both eyes are required during information collection. However, existing domestic literature predominantly conducts "single vision" research based on Hering' s law. When children with autism spectrum disorder and control group children watched videos of different emotions, an eye tracker recorded their eye movements with high precision. After targeted filtering of various noises in the high-precision data, changes in binocular disparity over time series were clearly revealed, forming a temporal eye movement analysis pattern. The results show: (1) Binocular disparity varies significantly with different emotional faces, supporting Helmholtz' s hypothesis and emphasizing coordination between the eyes; and (2) Significant differences in binocular disparity exist between the two groups across all emotional faces, further revealing the perceptual specificity of children with autism.

Keywords: Binocular coordination; Helmholtz' s hypothesis; Temporal eye movement analysis; Filtering; Autism Spectrum Disorder (ASD)

1. Introduction

Humans possess two eyes yet perceive a single, unified world. To maintain this unity, both eyes require precise, systematic control and coordination to align their foveae on approximately the same target—a process known as binocular coordination. This concept emphasizes the mutual cooperation and accommodation between the eyes prior to the formation of subjective "single vision" (King, 2011; Blythe et al., 2006; Kirkby et al., 2008; Yang & Kapoula, 2003). The quantitative metric for assessing binocular coordination is binocular disparity: the magnitude of difference between the visual images received by the two eyes.

Nevertheless, domestic research predominantly builds upon the concept of "single vision," treating both eyes as a unified organ that moves in perfect synchrony with convergent gaze at a single point. This conceptual limitation extends to research methodologies. For instance, studies on visual perception frequently employ the "Cyclopean Eye" (the average of left and right eye coordinates) or data from a single eye (left or right). Moreover, widely used eye trackers such as EyeLink, Tobii, and IView, along with their accompanying software, are designed to provide only monocular-related metrics and data processing procedures (see relevant manuals for details). Additionally, the limited domestic literature on interocular visual differences suffers from inconsistent terminology, including terms like fixation disparity, parallax, fixation parallax, fixation deviation, and fixation point distance (Chen, Chen & Zhao, 2016).

2. Binocular Coordination

2.1 Domestic and International Research

In terms of research content, the emphasis on "single vision" manifests in focusing all psycho-cognitive functions of vision on high-level processing after binocular information fusion, such as depth perception and binocular rivalry. Some researchers even implicitly consider binocular disparity an inherent, unchanging physiological attribute. For example, Wang and Wang (2007) emphasize that the interocular distance in head distribution determines binocular coordination (the magnitude of binocular disparity).

International research has long recognized and explicitly demonstrated that the eyes do not fixate on identical points during visual processing, even for single characters or points (Kirkby et al., 2008; Paterson et al., 2009; Kirkby et al., 2010). Furthermore, international studies have identified patterns of interocular coordination during the saccade-fixation cycle: when a fixation point is about to shift (i.e., saccade onset), one eye (the abducting or exploring eye) finishes processing the original fixation with its fovea and begins searching for the next potential fixation point, thus leaving first, while the other eye (the adducting or following eye) departs after a small time lag (Collewijn et al., 1988; Vernet & Kapoula, 2009). Consequently, interocular distance first increases during saccades, then decreases to some extent. When both eyes reach the next fixation point, binocular disparity undergoes a process of initial increase followed by decrease (Vernet & Kapoula, 2009; Yang & Kapoula, 2003; Collewijn et al., 1988). After collecting sufficient information, the behavioral pattern of both eyes enters the next cycle.

However, existing international research on interocular coordination is confined to small time scales in laboratory settings, preventing in-depth investigation under large time-scale (semi-)natural conditions. For instance, whether and how interocular coordination changes across different tasks remains unexplored. Such changes are not merely physiological but may also entail psychological significance. Kirkby et al. (2008) emphasized in their review that the psychological meaning of binocular coordination requires confirmation and specific investigation.

2.2 The Roots of "Single Vision" and Research Methodology: Hering' s Law and Helmholtz' s Hypothesis

Domestic research limitations in "single vision"and international research confinement to laboratories are deeply rooted in the century-long debate between two hypotheses about interocular relationships—Hering' s hypothesis and Helmholtz' s hypothesis. Helmholtz' s hypothesis, proposed by von Helmholtz in 1962, suggests that interocular connection is not a mandatory anatomical mechanism but rather modifiable through will alone—learnable and trainable. This hypothesis was subsequently challenged by Ewald Hering, who proposed Hering' s hypothesis (Hering, 1977): "When considering the influence of eye movements on vision, both eyes can be treated as a unified organ (operated by the nervous system)," like a person pulling both reins of a horse simultaneously. Consequently, research often assumes both eyes function as a single organ with synchronized movements—i.e., "single vision."

Due to the limited precision of early research instruments, most studies supported Hering' s hypothesis (King & Zhou, 2000; King, 2011). This support led to its widespread acceptance, transforming the hypothesis into Hering' s law of equal innervation (Howard & Rogers, 1995).

2.3 Temporal Sequence Analysis: Continuous Analysis in (Semi-)Natural Contexts

Constrained by the "single vision" concept, research paradigms on binocular coordination both domestically and internationally remain inadequate. Domestic studies primarily manipulate the differences between two images presented to each eye to control binocular disparity, a paradigm that is rigid, passive, and suffers from low ecological validity. Although international research on binocular coordination has achieved comprehensive development, it remains confined to laboratories, extracting individual eye movement features within small time scales (typically in milliseconds, with total duration under 1000ms) for short-cycle investigations of saccade-fixation cycles. This paradigm cannot accommodate natural (or semi-natural) contexts outside laboratories, where eye movements occur across large time scales (over 1s), continuously, and with mutual influence across time periods.

Faced with these challenges, the naturalistic, bidirectional, dynamic, large time-scale, continuous, and coherent characteristics of eye trackers become prominent. The present research leverages these advantages to seek eye movement quantification metrics for binocular disparity within dynamic video materials—specifically, inter-fixation distance, using the pixel distance between the two eyes' fixation points as an indicator of the magnitude of interocular visual difference (Chen, Chen & Zhao, 2016; Gao, Chen & Lin, 2017; Li, 2017). However, these studies have not fully captured the dynamic nature of binocular disparity—its unfolding over time series during task completion.

3. Specificity of Binocular Disparity in Children with Autism Spectrum Disorder

In searching for specific characteristics of autism, domestic research has found that children with Autism Spectrum Disorder (ASD) exhibit significantly different inter-fixation distances (i.e., binocular disparity) compared to typically developing children when viewing animated social videos (not involving depth perception), a finding repeatedly confirmed (Chen, Chen & Zhao, 2016; Gao, Chen & Lin, 2017; Li, 2017). Nevertheless, existing research paradigms cannot advance further investigation because they cannot answer how binocular disparity manifests in naturalistic conditions such as reading, picture viewing, or film watching (not involving depth perception). If binocular disparity exists uniformly during continuous visual processing, it would represent a relatively fixed physiological characteristic; otherwise, it is variable. If variable, are the changes completely random or do they occur systematically according to specific causes? If the former, binocular disparity retains physiological significance but is relatively stable rather than absolutely constant. If binocular disparity changes systematically according to specific causes, clarifying this relationship would establish its psychological meaning.

Further investigation into the specificity of binocular disparity in children with ASD using high-precision instruments can retest the two major hypotheses while developing a research paradigm for binocular coordination with high flexibility, ecological validity, proactivity, and large time scales—temporal analysis of eye movement data.

Practically, the issue of specificity in binocular disparity among children with ASD requires further clarification. Theoretically, domestic researchers are constrained by their lack of understanding of the historical origins of "single vision," while international binocular coordination research remains confined to laboratories. To address these theoretical challenges, developing a temporal analysis model based on eye movement data is essential.

3. Research Methods

3.1 Data Collection

The data for this study were derived from Chen et al. (2016). The experimental design employed a 2 (participant type: ASD vs. TD) × 3 (task type: different emotional faces [happy, sad, and fear]) factorial design. Video clips were presented to participants in random order to balance position effects. Data generation involved recording the coordinates of both eyes in children with Autism Spectrum Disorder (ASD) and typically developing (TD) children while they watched animated clips (excerpted from *Transport Cars*, Golan et al., 2010) using a Tobii eye tracker, then calculating the pixel distance between the two eyes' fixation points as binocular disparity. Data processing was conducted using MATLAB R2014a and SPSS 20 software.

3.2 Filtering Analysis of Raw Eye Movement Data

Before fully leveraging the advantages of eye trackers in binocular disparity research, one critical issue must be addressed—noise in eye movement data. Due to the high precision of eye tracking, data are easily affected by environmental noise, instrument conditions, blinking, head movements, and other factors (Munn et al., 2008). This noise is characterized by large amplitude and sudden pulses. Another portion originates from eye movements themselves: microtremors, drifts, and jitter. These eye movement features serve only physiological adaptation functions and are not essential for cognitive processing (Møller et al., 2006), exhibiting randomness, small amplitude, and high frequency.

First, filtering of large-amplitude noise. For outliers in data trends, a clipping median filter was applied for removal, followed by replacing the excised values with the median of adjacent data points (Olsen, 2012). Specifically, if a data value at a given time point exceeded a certain threshold, it was replaced by the median of data within a certain range of the adjacent region. Based on empirical trial-and-error filtering, 150 (units: pixels, hereinafter) was selected as the amplitude threshold for the clipping filter, with a step size of 5. Under these parameters, data trends were displayed most clearly. [Figure 1: see original paper] compares the data before and after median filtering for a TD child: noise was removed while overall trends became more pronounced, though some noise remained. [Figure 2: see original paper] illustrates the overall trends for both participant groups before and after clipping median filtering, revealing that after noise removal, data trends became clearer and the data range was significantly reduced (from approximately 0-200 to 10-60). Due to extremely dense detailed fluctuations, trends remained somewhat unclear.

Second, filtering of random noise. When analyzing multiple samples, noise from physiologically adaptive eye movements becomes amplified through superposition, masking the signal (as shown in the lower panel of [Figure 2: see original paper]). Since this noise is largely random, a mean filter from linear filtering was applied (Farmer & Sidorowich, 1991). Mean filtering replaces a value with the mean of data within a certain range of nearby values to smooth the trend. Without specific reference information for filter steps, the data collection frequency (60 Hz) was used as the filter step length, examining data trends in one-second units. As shown in [Figure 3: see original paper] and [Figure 4: see original paper], post-filtering data trends became more prominent and clear while preserving the trends, making specific information about differences over time series highly discernible.

4. Results

4.1 Filtering Effectiveness Analysis

Chen et al. (2016) found that the binocular disparity of ASD and TD children differed significantly in multidimensional scaling (MDS) space. To verify the filtering effectiveness in this study, data after both filtering stages were compared with raw data. To clearly demonstrate filtering effects in two-dimensional space while meeting all MDS criteria, we randomly selected one of the three video clips for comparison. As shown in [Figure 5: see original paper], the two-dimensional MDS distributions of both groups' data were reasonable at each stage (all three MDS analysis metrics were appropriate: Stress$<$0.25, DAF$>$0.9). From panel a to c, the boundary between the two groups became increasingly neat and clear. Group differences were significantly enhanced after filtering, indicating good filtering effectiveness.

4.2 Temporal Sequence Analysis of Both Groups and Three Emotional Faces

After two stages of filtering, the specific nature of differences could be examined. As shown in [Figure 4: see original paper], we can first observe that overall, ASD children exhibited larger binocular disparity than TD children, with greater fluctuation, though some crossover or largely consistent regions also existed.

[Figure 6: see original paper] presents the correspondence between binocular disparity and events over time series. Second, the difference in binocular disparity between ASD and TD groups was not uniformly distributed. Through event comparison, we found: (1) When screen content showed scenes, the binocular disparity trends of ASD and TD groups were comparable, with ASD even showing smaller disparity than TD in some portions (as shown in [Figure 6: see original paper], rectangular boxes containing objects, backgrounds, and distant profiles, which are essential for story development); (2) When different emotional faces appeared on screen, the two groups showed different changing trends. After happy faces appeared, TD children's binocular disparity decreased relative to before; after sad faces, it increased relative to before; and during fear faces, it increased significantly, approaching ASD levels. In contrast, ASD children showed relatively consistent trends across different emotional faces, with binocular disparity significantly increasing in all cases (as shown in [Figure 6: see original paper], square boxes containing frontal faces occupying over 80% of the screen); (3) When emotional faces appeared, ASD children showed relatively greater trend fluctuations.

4.3 Two-Way ANOVA of Both Groups and Three Emotional Faces

To further verify the descriptive conclusions from temporal sequence analysis of binocular disparity, data from periods when emotional faces (happy, sad, and fear) appeared were extracted from the three video clips (as shown in the square boxes in [Figure 6: see original paper]) for quantitative analysis. To maintain the integrity of each video story and facilitate comprehension, the durations of emotional face presentations were not identical during material creation, resulting in slightly different data quantities for each emotion. The means and standard deviations of binocular disparity for both groups across the three emotional faces are shown in Table 1. Two-way ANOVA results indicated significant main effects for participant type, $F(1, 4870) = 5117.78$, $p < 0.001$, $p^2 = 0.52$, and for emotional face type, $F(2, 4870) = 367.65$, $p < 0.001$, $p^2 = 0.13$, as well as a significant interaction, $F(2, 4870) = 738.87$, $p < 0.001$, $p^2 = 0.23$.

Table 1 Binocular Disparity of Both Groups Across Three Emotional Faces (M ± SD)

Participant Type	Happy (n=896)	Sad (n=802)	Fear (n=740)
TD Children	23.52 ± 1.49	25.23 ± 1.20	27.38 ± 3.50
ASD Children	31.68 ± 4.24	35.96 ± 3.40	29.09 ± 4.74

Note: Data were rounded to two decimal places.

Simple effects analysis revealed that ASD children' s binocular disparity was significantly greater than TD children' s across all three emotional faces (p <

0.01), as shown in [Figure 7: see original paper]. Among ASD children, binocular disparity differed significantly across the three emotional faces ($p < 0.01$). Post-hoc tests indicated that ASD children’ s binocular disparity was significantly smaller for happy than fear ($p < 0.01$), and significantly smaller for fear than sad ($p < 0.01$). For TD children, binocular disparity was significantly smaller for happy than sad ($p < 0.01$), and significantly smaller for sad than fear ($p < 0.01$). Thus, as emotions transitioned from positive to neutral to negative (happy-sad-fear), TD children’ s binocular disparity increased significantly, whereas ASD children’ s binocular disparity first increased then decreased, with the smallest value occurring for fear (as shown in [Figure 7: see original paper]).

5. Discussion

5.1 Temporal Filtering Analysis of Eye Movement Data: Event-Related Binocular Disparity (ERBD)

By introducing filtering methods from signal processing, relevant issues can be resolved. This study’ s application of clipping median and mean filtering simplified, clarified, and highlighted the trends of both groups over time series (as shown in [Figure 3: see original paper], [Figure 4: see original paper], and [Figure 5: see original paper]). The MDS analysis after filtering ([Figure 5: see original paper]) shows that from raw data through first and second filtering, the boundary between ASD and TD individuals became increasingly clear with deeper filtering, yielding better discrimination and excellent effectiveness. The two-stage filtering produced good results.

Implementing temporal sequence analysis of binocular disparity eye movement data is crucial for binocular coordination research. First, only temporal changes in binocular disparity can reveal coordination performance during the dynamic process of visual processing, highlighting the “coordination” aspect of binocular coordination. Existing domestic research related to binocular coordination has focused on the concept of binocular disparity itself, employing a rigid paradigm of artificially controlling interocular image differences, which emphasizes disparity rather than coordination.

Second, describing binocular disparity over time series allows clearer understanding of whether and when binocular disparity changes. By comparing trends before and after events, we can discuss how specific events affect binocular coordination. In [Figure 6: see original paper], we can not only intuitively observe that ASD children’ s binocular disparity is generally greater than TD children’ s (dashed line above solid line), but also clearly see changes in binocular disparity around events. For example, before happy faces appeared, group differences were minimal; after happy faces appeared, ASD children’ s binocular disparity suddenly increased while TD children’ s decreased; during happy face presentation, both groups’ binocular disparity fluctuated rather than remaining absolutely constant, allowing future research to investigate the specific causes of such fluctuations; after happy face presentation, both groups’ binocular disparity showed regression trends. This temporal analysis approach compensates for the insufficient spatial information (where) analysis in existing eye movement research (Falck-Ytter, 2010). We hope temporal eye movement analysis can become a research method like event-related potentials—event-related eye movements. While event-related potentials tend to reflect higher-level processing, event-related eye movements reflect primary processing, and with appropriate design and comparison, we can shed light on the black box from low-level to high-level processing.

Finally, this temporal analysis paradigm permits diverse experimental materials, greatly enhancing ecological validity and expanding future research directions. The coherent analysis of animated video materials in this study demonstrates this paradigm' s strengths. Existing eye movement research using fixation analysis can only conduct static analyses with picture materials, requiring video materials to be decomposed frame-by-frame for static analysis. The temporal analysis paradigm offers unique advantages for analyzing videos and other materials, and is equally applicable to picture and reading studies. For example, it enables investigation of processing at different time points for the same stimulus, which previous paradigms could not achieve. Whether expanding existing static picture or reading research or broadening experimental materials, the temporal analysis paradigm substantially enhances ecological validity.

5.2 Emphasis on Helmholtz' s Hypothesis

Helmholtz' s hypothesis has received indirect support from developmental and rehabilitation training studies on binocular coordination, suggesting that binocular coordination appears driven by visual experience and based on neural plasticity/maturation. Nevertheless, Helmholtz' s hypothesis still lacks more direct support (King, 2011; Coubard, 2015). This study, employing different experimental materials (dynamic social videos) and data analysis methods, found (as shown in [Figure 6: see original paper]) that both groups' binocular disparity changed with task demands (object scenes vs. face scenes; among different emotional face scenes). Relatively speaking, the three emotions differed in difficulty (Gross, 1991), with recognition rates decreasing significantly from happy to sad to fear (Ma et al., 2015; Golan et al., 2010), indicating that task difficulty affected binocular disparity. In [Figure 6: see original paper], typically developing children also showed gradually increasing binocular disparity with increasing emotional negativity.

5.3 Specificity of ASD Binocular Coordination in Emotional Face Processing

Lin and Zhang (2010) included perceptual specificity as a dimension in their self-developed "Questionnaire on Functional Domain Development of Children with Autism," and other studies (Chen, Chen & Zhao, 2016; Gao, Chen & Lin, 2017; Li, 2017) have reported similar findings. However, these studies did not further investigate that binocular coordination shows more pronounced specificity in emotional face processing. First, across the three emotional faces, ASD children' s binocular disparity was significantly greater than TD children' s, with greater variability in ASD. Second, while TD children' s binocular disparity increased significantly with emotional negativity, ASD children' s binocular disparity first increased then decreased significantly, with the smallest value occurring for fear.

6. Conclusion

1) Clipping median filtering and mean filtering can effectively eliminate noise affecting analysis results in eye movement data while making temporal trends in binocular disparity more intuitive and pronounced.

2) When viewing social scenario videos, binocular disparity changes over time series with task difficulty, indirectly indicating that individuals' will can control binocular disparity changes and directly supporting Helmholtz' s hypothesis.

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Note: Figure translations are in progress. See original paper for figures.