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Cite this article: Wood ML, Waterman AH, Wright J, van den Bree M, Mon-Williams M, Hill L. 2025 Ethnic differences in sensorimotor processing: a longitudinal study using the Born in Bradford cohort. *R. Soc. Open Sci.* **12**: 250882. https://doi.org/10.1098/rsos.250882

Received: 7 May 2025
Accepted: 28 October 2025

Subject Category:
Psychology and cognitive neuroscience

Subject Areas:
psychology, developmental biology

Keywords:
sensorimotor processing, kinematic analysis, ethnicity, motor development, longitudinal data, cohort study

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Supplementary material is available online at https://doi.org/10.6084/m9.figshare.c.8172275.

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Ethnic differences in sensorimotor processing: a longitudinal study using the Born in Bradford cohort

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Sensorimotor processing is a fundamental neurodevelopmental skill that underpins many higher order cognitive abilities. Early ethnic differences in motor behaviour have been found. However, the reported disparities have involved subjective measures and can be explained via differences in socioeconomic status or cultural biases. For the first time, to our knowledge, we were able to investigate ethnic population differences longitudinally with objective kinematic measures of sensorimotor processing. Sensorimotor processing was investigated in 1340 children from the 'Born in Bradford' cohort. Data were collected at two timepoints (age 4–5 years and 7–9 years). Even after controlling for socioeconomic differences, the Pakistani-heritage population demonstrated quantitatively lower levels of sensorimotor processing relative to children of White British heritage at both timepoints. These differences were equivalent to six months' developmental progress. However, ethnic differences decreased over time. The decreases over time suggest that sensorimotor skill deficits can be mitigated through education and daily learning activities. Our findings suggest sensorimotor measures can provide a behavioural marker of neurodevelopmental status and have potential for identifying children who need early learning support. The ethnic differences are not well explained by socioeconomic factors, with genetic and environmental differences providing a potential hypothesis for future testing.

1. Introduction

Sensorimotor skills are a critically important feature of healthy childhood development. Children with motor deficits often struggle to complete basic childhood activities of daily living (e.g. dressing, feeding, playing), which can lead to poor self-esteem and increased risk of mental health difficulties [1,2]. Furthermore, without these core skills, children are less likely to be active and thus have an increased risk of obesity and poor physical health [3,4].

The transformation of perceptual information for the purpose of generating skilled movement is one of the most fundamental neurological processes found within the animal kingdom [5]. The consequences of impairments in this ability, defined as sensorimotor processing, are profound. Sensorimotor processing is necessary for effective interactions with the environment—interactions that support learning, the formation of social bonds and physical development [6–16]. Moreover, Piagetian theory suggests that sensorimotor development is a necessary precursor to the acquisition of higher-order cognitive abilities [17]. Neurobiological models likewise suggest that the neural circuits responsible for sensorimotor processing are the 'building blocks' of complex and abstract cognitive skills [18–21]. This can explain why immature sensorimotor processing is associated with lower academic achievement [22–24].

Sensorimotor processing requires maturation of a wide range of distinct brain regions such as the primary motor cortex, prefrontal cortex, as well as non-cortical structures such as the basal ganglia, cerebellum and thalamus [25]. This suggests that assessment of sensorimotor processing could be a useful biomarker of neural development. Indeed, previous research has found links between neurodevelopment and sensorimotor processing. For example, Neumane *et al.* [26] showed that preterm infants have impaired sensorimotor brain networks.

Ethnic differences in motor function have been reported previously [27–36]. However, these studies have not used robust objective measures of sensorimotor processing (introducing cultural biases) and/or have not controlled for socioeconomic position (SEP). One study that did control for socioeconomic circumstances found no significant ethnic differences in the parent-reported attainment of fine motor milestones [33]. We therefore set out to contribute robust evidence to the question of whether ethnic differences exist in objective measures of sensorimotor performance and, if so, whether these differences remain after controlling for socioeconomic status and whether they change over time.

2. Material and methods

2.1. Participants/design

Secondary data analysis from the Born in Bradford (BiB) longitudinal birth cohort study was undertaken. Based in the City of Bradford, UK, BiB recruited 12 453 pregnant mothers at 26–28 weeks gestation during routine clinical visits to the city's main maternity unit between 2007 and 2011 [37,38]. The BiB cohort is particularly suitable for studying ethnic differences owing to the high ethnic density of South Asian (predominantly Pakistani) individuals in the cohort (50.1%). Details regarding initial recruitment to BiB can be found elsewhere [37]. Within the current study, to maintain appropriate statistical power, only those from White British or Pakistani-heritage ethnic backgrounds were retained for analysis.

Sensorimotor processing was recorded during two data collection waves. In the first, children were 4–5 years of age (n = 3444) [39], while a larger, second wave was conducted later when children were 7–9 years old (n = 9604) [40]. For the present analyses, we used a complete-case approach, including only children with data available at both waves and with information on ethnicity and SEP. This strategy enabled direct longitudinal comparisons of ethnic differences in sensorimotor processing.

First, children with missing SEP data were omitted (n = 1123). Next, we retained only those with observations at both timepoints, ensuring that trajectories reflected actual within-child changes rather than model-estimated values (n = 2712 omitted). Finally, we excluded children with missing ethnicity data (n = 246) or whose ethnicity was recorded as other than White British or Pakistani (n = 400). The final sample included 1340 children. See table 1 for a breakdown of the sample demographics.

2.2. Dependent variables

Sensorimotor processing was measured via a tablet-based, objective standardized assessment battery, the Clinical-Kinematic Assessment Tool (CKAT) [41,42]. CKAT consists of three sensorimotor tasks:

Table 1. Sample demographics. (s.d., standard deviation; SEP, socioeconomic position.)

	whole sample	White British	Pakistani
n	1340	393	947
mean age: 4–5 years (s.d.)	4 years, 6 months (6 months)	4 years, 6 months (6 months)	4 years, 6 months (6 months)
mean age: 7–9 years (s.d.)	8 years, 2 months (9 months)	8 years, 3 months (9 months)	8 years, 1 month (8 months)
handedness: right (%)	1203 (89.8%)	344 (87.5%)	859 (90.7%)
sex: female (%)	676 (50.4%)	201 (51.1%)	475 (50.2%)
SEP (%)			
most deprived (SEP1)	218 (16.3%)	74 (18.8%)	144 (15.2%)
benefits but coping (SEP2)	489 (36.5%)	73 (18.6%)	416 (43.9%)
employed and no access to money (SEP3)	218 (16.3%)	74 (18.8%)	144 (15.2%)
employed and not materially deprived (SEP4)	232 (17.3%)	120 (30.5%)	112 (11.8%)
least deprived and most educated (SEP5)	183 (13.6%)	52 (13.2%)	131 (13.8%)

tracking, aiming and steering (see figure 1). To complete each of the tasks, appropriate and distinct sensorimotor transformations are required. The battery has the temporal and spatial accuracy of laboratory-based motion capture systems while allowing testing at scale within school settings [41]. The device uses kinematic methods which are more objective than traditional assessment methods such as parent- or teacher-reported questionnaires (e.g. Developmental Coordination Disorder Qustionnaire [DCD-Q'07] [43]) or observational tools (e.g. Test of Gross Motor Development-2 [TGMD-2] [44]; Movement Asssessment Battery for Children-2 [MABC-2] [45]), which can be confounded by human error, biases and inaccuracies [2,42,46,47]. CKAT captures three distinct, fundamental sensorimotor transformations: using predictive models to track a moving target (tracking), performing online feedback corrections to respond to moves between targets (aiming) and using feedforward control to guide movement along a path (steering). The battery was completed using a stylus pen on a touch-screen device. Full details regarding CKAT and its testing protocol are reported elsewhere [40].

CKAT records task-relevant kinematic features of each movement at 120 Hz, which are transformed to describe the spatial and temporal qualities of sensorimotor processing. In turn, hundreds of individual indices are produced by the battery, describing the minutiae of each movement. To avoid arbitrary selection of which kinematic indices to include within analyses, a data reduction approach was implemented to produce several latent kinematic variables for each task, the methods of which are reported elsewhere [48]. A weighted mean latent score was calculated for each task, which was then standardized (z-scored) and mean-centred. These standardized scores were subsequently averaged across all three tasks to produce a single overall score. Higher scores indicate more spatially and temporally accurate sensorimotor performance. Because the scores were centred around the sample mean, they span both positive and negative values, with zero representing average performance for the population.

We chose to focus on a broad composite score rather than disaggregated indices, as this provides a more parsimonious and practically interpretable measure of sensorimotor performance. In applied educational and clinical contexts, such summary measures are more accessible and meaningful for practitioners and teachers, while still retaining sensitivity to group-level differences. Given that this is, to our knowledge, the first study to examine ethnic differences in sensorimotor processing using this large longitudinal cohort, our priority was to establish the broader picture before delving into specific subcomponents. We acknowledge that future work should examine which kinematic elements may be driving these group differences in more detail.

2.3. Independent variables (predictors and covariates)

Ethnicity and SEP were self-reported by mothers on recruitment to BiB [37]. SEP was measured via a latent variable comprising 19 individual indicators of socioeconomic circumstance [49]. In addition to

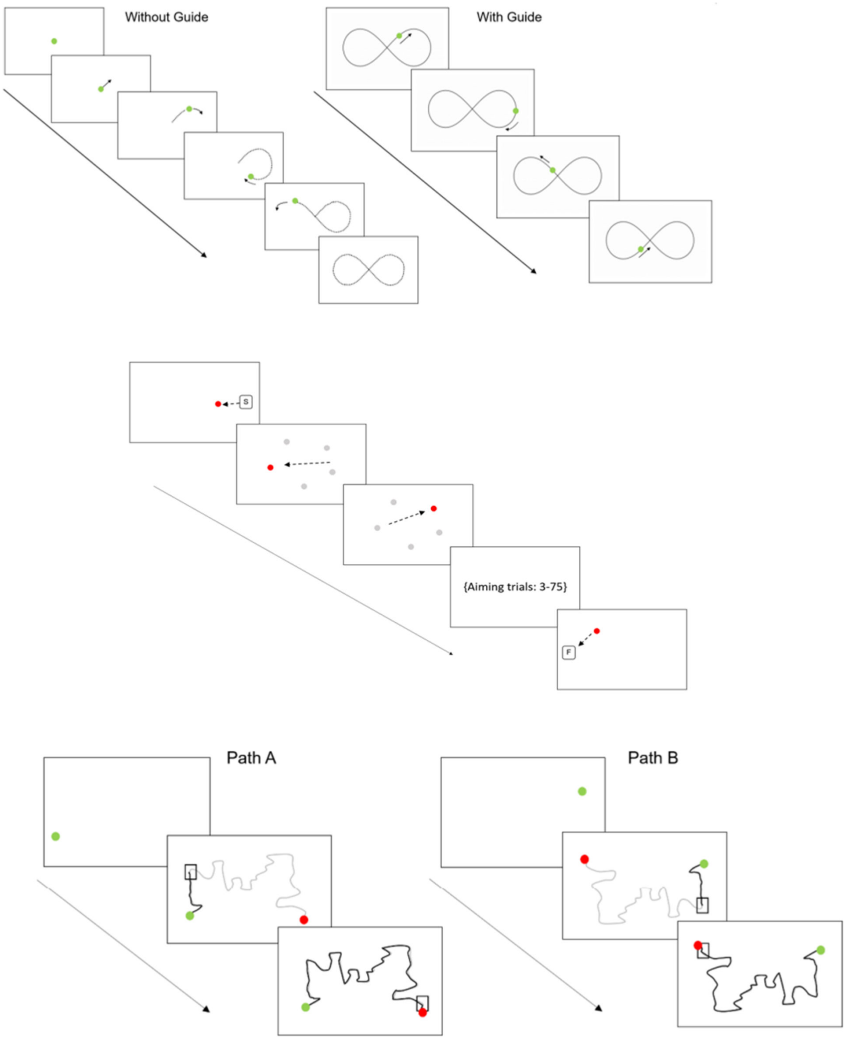

Figure 1. Tracking, aiming and steering tasks on the CKAT.

traditional indicators, such as maternal education or employment status, it also included a measure of subjective poverty and whether the mother felt she was able to afford various items, services or provisions (e.g. 'able to afford money to make regular savings of £10 a month') to provide a more holistic view of socioeconomic resources. A multidimensional indicator of SEP was considered appropriate to capture this construct's multifaceted nature, reducing risks of ethnic or cultural biases that may arise from relying on any one single measure (e.g. education level when mothers may be educated outside of the UK [49–51]). The resultant SEP variable had five ordinal levels (SEP1, most deprived; SEP2, benefits but coping; SEP3, employed and no access to money; SEP4, employed and not materially deprived; and SEP5, least deprived and most educated). Self-reported handedness was obtained during administration of the CKAT battery, while age and gender were obtained from education records.

2.4. Statistical analysis

One linear regression model and two linear mixed effects (LME) models were conducted to investigate how the development of sensorimotor processing between early- (4–5 years) and middle-childhood (7–9 years) differed across the two ethnic groups (White British; Pakistani-heritage). The linear regression model included only ethnicity as the predictor and the overall score at 4–5 years as the outcome variable (model 1). Model 2 included timepoint × ethnicity as an interaction term. Timepoint was a fixed effect that was nested within participants, and child ID was a random effect that accounted for individual differences. Finally, model 3 was an updated version of model 2, which adjusted for covariates (age, gender, SEP and handedness).

For SEP, the reference category was 'most deprived' (SEP1), against which all other SEP classes were compared. All LME models used maximum likelihood estimations. Effect sizes were calculated to evaluate the effect of timepoint using Pearson's *r*. Where significant interactions were found, planned contrasts were conducted to identify how ethnic differences varied over time, with Bonferroni corrections applied. All analyses were conducted in R (version 4.1.2). Please see electronic supplementary material for analytic code.

3. Results

The first analysis explored the presence of ethnic differences at 4–5 years (model 1). Next, an interaction with timepoint was included (model 2) to understand the relationship over time.

Model 1 revealed ethnicity was significantly associated with sensorimotor performance at 4–5 years old ($F_{1,864}$ = 18.66, $p < 0.001$), with White British children (M = −0.52, s.d. = 0.50) showing increased scores on the sensorimotor assessment relative to their Pakistani-heritage peers (M = −0.69, s.d. = 0.53), see table 2.

In model 2, main effects were also found for timepoint (b = 0.94 [0.90, 0.98], $p < 0.001$) and ethnicity (b = 0.17 [0.09, 0.24], $p < 0.001$). Children's sensorimotor processing was significantly improved at 7–9 years (M = 0.27, s.d. = 0.28) compared to 4–5 years (M = −0.64, s.d. = 0.52) and, overall, White British children (M = −0.10, s.d. = 0.57) showed higher scores than their Pakistani-heritage peers (M = −0.22, s.d. = 0.63). A significant interaction between ethnicity and timepoint was also found (b = −0.09 [−0.17, −0.02], p = 0.016). Post-hoc pairwise comparisons showed there was a significant difference between Pakistani-heritage and White British children at 4–5 years (b = −0.17 [−0.27, −0.07], $p < 0.001$, r = 0.15). A significant ethnic difference remained at 7–9 years, but the magnitude of this effect reduced (b = −0.08 [−0.13, −0.02], p = 0.002, r = 0.12). This is illustrated in figure 2.

Model 3, with the addition of covariates, found main effects which suggested better performance for 7–9 year olds compared to 4–5 year olds (b = 0.71 [0.62, 0.80], $p < 0.001$, r = 0.18); White British compared to Pakistani-heritage children (b = 0.16 [0.08, 0.23], $p < 0.001$, r = 0.14); SEP3 compared to the 'most deprived' SEP1 (b = 0.07 [0.01, 0.13], p = 0.019, r = 0.08). Increasing age also predicted better task performance (b = 0.06 [0.04, 0.09], $p < 0.001$, r = 0.18). Neither handedness (p = 0.499), nor gender (p = 0.420) were significant predictors of performance. Model 3 also showed that the same significant interaction between ethnicity and timepoint persisted (b = −0.10 [−0.18, −0.03], p = 0.009). Similarly, pairwise comparisons revealed that there was a significant difference between Pakistani-heritage and White British children at 4–5 years (b = −0.16 [−0.06, −0.26], $p < 0.001$, r = 0.14) and this remained so at 7–9 years (b = −0.06 [−0.00, −0.11], p = 0.037, r = 0.09). The effect sizes for ethnicity were relatively small, with White British children scoring 0.12 higher than Pakistani-heritage children on average. To provide a rough interpretation of the magnitude of group differences, we calculated the difference in overall sensorimotor z-scores between White British and Pakistani-heritage children and converted this to an approximate age-equivalent difference based on longitudinal growth in the cohort. The average yearly improvement in overall sensorimotor score was 0.24, yielding an estimate of approximately six months of typical developmental progress. We emphasize that this figure is illustrative of the magnitude of the difference rather than a formal developmental delay, and it reflects relative differences in performance on the CKAT tasks rather than clinical impairment.

4. Discussion

We investigated the developmental trajectory of sensorimotor processing between early- and middle-childhood and explored how these trajectories differed as a function of ethnicity. Children's sensorimotor processing significantly improved between early- (4–5 years) and late- (7–9 years) childhood. White British pupils showed more developed sensorimotor processing at both 4–5 years and 7–9 years, compared to their Pakistani-heritage peers. In contrast to previous research (e.g. [33]), these differences persisted even after controlling for socioeconomic circumstances. This suggests that ethnic differences cannot be explained solely by the socioeconomic inequalities often associated with ethnic minority groups [52,53]. Importantly, the observed age-related developmental gap—Pakistani-heritage children performing approximately six months behind their White British peers—combined with the critical role of sensorimotor skills in early childhood, indicates that this difference is meaningful. As noted earlier, this does not constitute a clinical developmental delay. Rather, it illustrates that even modest

Table 2. Regression table showing the three models conducted. (s.e., standard error; SEP, socioeconomic position. Bold values, $p < 0.05$.)

	B	s.e.	*t*	*p*
model 1				
intercept	−0.69	0.02	−33.05	**<0.001**
ethnicity: White British	0.17	0.04	4.32	**<0.001**
model 2				
intercept	−0.69	0.02	−33.05	<**0.001**
timepoint: 7–9 years	0.94	0.02	46.04	**<0.001**
ethnicity: White British	0.17	0.04	4.32	**<0.001**
timepoint: 7–9 years × ethnicity: White British	−0.09	0.04	−2.41	**0.016**
model 3				
intercept	−1.00	0.07	−14.98	**<0.001**
timepoint: 7–9 years	0.71	0.05	14.86	**<0.001**
ethnicity: White British	0.16	0.04	4.14	**<0.001**
SEP2: benefits but coping	−0.01	0.03	−0.37	0.711
SEP3: employed with no access to money	0.07	0.03	2.34	**0.019**
SEP4: employed but not materially deprived	0.00	0.03	0.11	0.915
SEP5: least deprived and most educated	0.05	0.03	1.59	0.112
gender: male	−0.01	0.02	−0.81	0.420
handedness: right	0.02	0.03	0.68	0.499
age	0.06	0.01	5.28	**<0.001**
timepoint: 7–9 years × ethnicity: White British	−1.00	0.04	−2.64	**0.009**

group-level differences may have practical implications for educational or intervention strategies, emphasizing the importance of monitoring sensorimotor development and providing support where disparities are observed.

This study represents an important first step in examining ethnic differences in sensorimotor development using objective kinematic measures. Our decision to focus on an overall composite score was intentional, as it provides a practically interpretable measure that is more meaningful for teachers and practitioners than a proliferation of highly specific indices. In applied educational and clinical contexts, broad indicators of sensorimotor development are valuable for identifying children who may require additional support. The fact that discrepancies emerged even at this composite level highlights the potential use of such measures for understanding children's sensorimotor—and by extension, neurodevelopmental—capacity at school entry. Moreover, because the composite was derived from over 10 kinematic indices (e.g. deceleration time, time to peak speed, path accuracy; see Wood *et al.* [48] for detail), we are confident that it captures a comprehensive snapshot of each child's sensorimotor processing.

From a theoretical standpoint, however, future research would benefit from unpacking the specific subcomponents of sensorimotor performance (e.g. precision, visual–motor integration, reaction time) to determine which elements contribute most to observed group-level differences. Such work would extend beyond the applied focus of the present study and provide richer insight into the developmental mechanisms underlying ethnic disparities in motor skills.

Some motor assessments, such as those which feature sport-specific activities (e.g. kicking a ball) or specific handwriting tasks, may be culturally biased (i.e. increased familiarity and/or cultural dependence) and thus contribute towards ethnic differences in motor skill [42]. Moreover, CKAT comprises novel tasks relying on fundamental sensorimotor processes and is therefore largely free from any such cultural biases [42]. Thus, cultural measurement biases do not appear to provide a satisfactory explanation for the ethnic differences found. Similarly, it could be argued that access to tablets within the home environment could influence performance on a task using a tablet device. While socioeconomic factors were controlled for, the extent to which tablet familiarity or cultural

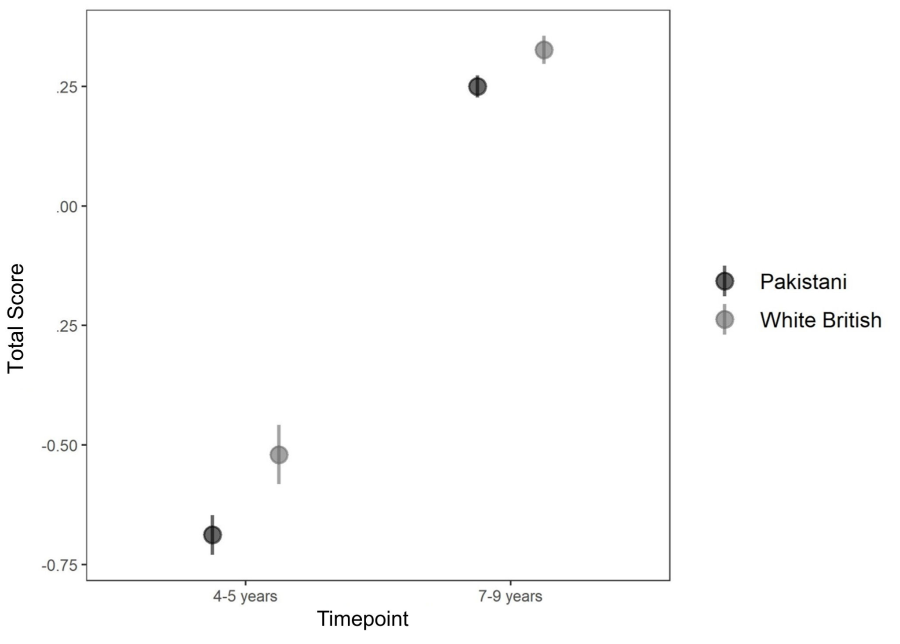

Figure 2. Mean overall score by ethnicity and timepoint. Error bars show 95% confidence intervals.

acceptance of screen time varies across groups remains an open question and warrants further investigation.

Another potential contributing factor is genetic load. Higher levels of autozygosity have been associated with a range of outcomes, including slower reaction times, lower educational attainment and increased risk for certain physical and mental health conditions [54–56]. Thus, autozygosity would be expected to interfere with neural development, and this would, in turn, impact sensorimotor processing. While we did not collect genetic data in this study and therefore cannot directly test this hypothesis, it represents a plausible factor that may influence neural and sensorimotor development.

Importantly, environmental and cultural factors are also likely to contribute to the observed ethnic differences in sensorimotor performance. For example, while socioeconomic factors were controlled for, variation in home stimulation and parental practices, such as the types of play, opportunities for fine and gross motor activities or encouragement of physical exploration, could influence early motor skill development [57–59]. Differences in early education experiences, including access to quality preschool or structured motor skill activities, may further shape sensorimotor trajectories [60,61]. Norms around physical play and recreational activities, including access to safe green space to play, can vary culturally, affecting the frequency and type of motor practice children engage in. Future research that incorporates genetic, environmental and familial measures will be necessary to disentangle the relative contributions of these factors and to understand how they interact to shape sensorimotor development across different ethnic groups.

It is important to note that the magnitude of the ethnic differences decreased between the two timepoints of the study. Humans have a remarkable propensity to learn new motor skills, and this reflects a large degree of plasticity in the sensorimotor neural architecture. In the UK, children spend an estimated 36–66% of class time engaged in fine motor activities in their early school years [62]. This allows children who start school with poorer sensorimotor processing (due to neural deficits and/or exposure to training opportunities) to begin catching up with their peers through day-to-day classroom activities [63]. Our findings thus suggest that early delays in children's neurodevelopment might be mitigated through exposure to a rich and stimulating educational environment. In turn, this provides yet further evidence that developmental delay in early life can be reduced through learning and exposure to a rich and diverse environment. Indeed, there is a wealth of evidence that children who receive timely and appropriate support can often thrive and reach their full potential despite delays in skill acquisition earlier in life [64–66].

A potential limitation of the study is the inclusion of only two timepoints. With only two waves, it is not possible to estimate more complex longitudinal models, such as latent growth curves, which require at least three timepoints to model individual differences in rates of change. Nevertheless, a new wave of CKAT data collection in the BiB cohort is underway as the children reach adolescence (Born in Bradford: Age of Wonder [67]), which will allow future research to investigate the subsequent trajectories of these ethnic differences. In addition, while most of the BiB participants are of White British or Pakistani heritage, future research may benefit from the investigation of additional ethnic groups to determine further ethnic disparities. We also did not have access to detailed measures of home environment, parental practices or beliefs. Consequently, we are unable to examine how these factors may contribute to the observed ethnic differences in sensorimotor performance. Future research that incorporates such data would allow for a more robust investigation of potential explanatory mechanisms and provide deeper insight into the development of ethnic differences in sensorimotor skills. Finally, subsequent research could explore ethnic differences in sensorimotor development as a function of environmental factors alongside genetics, for example, by incorporating linked healthcare records on genetic anomalies which have already been collected for a proportion of the BiB cohort.

5. Conclusion

This is, to our knowledge, the first published study to demonstrate ethnic differences in sensorimotor processing using an objective, kinematic assessment, while also controlling for socioeconomic differences. Ethnic differences were found between White British and Pakistani-heritage children, with White British children showing higher scores on the task. Most importantly, these differences were equivalent to six months' developmental difference in sensorimotor processing, highlighting that this difference is not trivial. However, there was a reduction in the magnitude of such differences over time. Thus, we suggest that immature neurodevelopment can be mitigated when children are provided with an adequate supportive learning environment. In addition, our findings provide support for the use of a computerized assessment of sensorimotor processing in childhood assessment and demonstrate its use in detecting subtle behavioural biomarkers of neurodevelopment. We propose that the assessment of sensorimotor processing on school entry using such a tool might provide vital insight into which children would benefit most from more targeted learning and developmental support.

Ethics. Ethical approval for the re-analysis of these data was granted by the University of Leeds ethics committee (reference: PSC-826). Ethical approvals for the Starting School data collection were obtained from ethics committees at the University of Leeds (reference: 13-0220) and the University of York (reference: 12/26). Ethical approval for data linkage within the BiB cohort was obtained from the Bradford Leeds Research Ethics Committee (reference: 07/H1302/112). Ethical approval for the data collection for the Primary School Years sweep was obtained from the NHS Health Research Authority's Yorkshire and the Humber–Bradford Leeds Research Ethics Committee (reference: 16/YH/0062) on 24 March 2016. All data were obtained via data requests from BiB's Executive Committee.

Data accessibility. Scientists are encouraged to make use of the BiB data, which areis available through a system of managed open access.

Before you contact BiB, please make sure you have read our Guidance for Collaborators. Our BiB executive review proposals on a monthly basis, and we will endeavour to respond to your request as soon as possible. You can find out about all of the different datasets which are available here (Our Data - Born in Bradford). If you are unsure if we have the data that you need, please contact a member of the BiB team (borninbradford@bthft.nhs.uk).

Once you have formulated your request, please complete the Expression of Interest form available here (How to Access Data - Born in Bradford) and email the BiB research team (borninbradford@bthft.nhs.uk). If your request is approved, we will ask you to sign a collaboration agreement; if your request involves biological samples, we will ask you to complete a material transfer agreement. Unfortunately, as the study uses secondary data analysis from BiB, I am unable to posit the datawithin data within an online repository as this will be in breach of the signed data sharing agreement.

The analytic scripts supporting this article have been uploaded as part of the electronic supplementary material [68].

Declaration of AI use. We have not used AI-assisted technologies in creating this article.

Authors' contributions. M.L.W.: conceptualization, data curation, formal analysis, investigation, methodology, visualization, writing—original draft, writing—review and editing; A.H.W.: funding acquisition, resources, supervision, writing—review and editing; J.W.: funding acquisition, resources, writing—review and editing; M.v.d.B.: writing—review and editing; M.M.-W.: funding acquisition, resources, software, supervision, writing—

review and editing; L.H.: conceptualization, funding acquisition, methodology, resources, supervision, validation, writing— review and editing.

All authors gave final approval for publication and agreed to be held accountable for the work performed therein.

Conflict of interest declaration. We declare we have no competing interests.

Funding. This paper presents independent research conducted as part of the lead author's doctoral degree, funded by the ESRC White Rose Doctoral Training Partnership Pathway Award (ES/P000745/1). The work was also partly funded by the National Institute for Health Research (grant number NIHR133648), UK Prevention Research Partnership (grant number MR/S037527/1), and the Medical Research Council (grant number MR/W014416/1).

Acknowledgements. 'Born in Bradford' is only possible because of the enthusiasm and commitment of the children and parents in BiB. We are grateful to all the participants, health professionals, and researchers who have made BiB happen.

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