scientific reports

OPEN

Investigating developmental changes in susceptibility to temporal audiovisual illusions on balance and sensorimotor function in children

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Balance and movement rely on multisensory input. In older adults, audiovisual integration—measured via the Sound-Induced Flash Illusion (SIFI)—has been linked to balance and motor performance, suggesting that multisensory perceptual measures may relate to functional motor abilities. This study explored whether similar links exist in childhood or emerge later in development. A total of 118 children aged 4–17 years of age completed (1) a balance task (standing on one leg, eyes open vs. closed), (2) a timed visuomotor task (maximum target hits in 2 min), and (3) the SIFI task (judging flashes paired with beeps at varying stimulus onset asynchronies, SOAs). Older children used vision more for balance, showed better visuomotor performance, and were less susceptible to SIFI illusions at longer SOAs, indicating developmental refinement in audiovisual integration. However, we found no strong evidence linking SIFI performance with balance or motor performance. Exploratory analyses revealed that children with dance training and those who found the task easier were slightly less susceptible to the illusion. These results suggest that links between multisensory integration and sensorimotor performance may not be present in early childhood or may require more sensitive measures to detect, offering a potential avenue for future research.

Keywords Audiovisual integration, Sound-induced flash illusion (SIFI), Balance, Visuomotor skill, Child development, Multisensory processing

Interacting with the world around us is inherently a multisensory experience. As you walk down the street, you use vision to guide your footsteps[1], receive auditory feedback from the sound of your steps on the pavement[2], and adjust your body weight distribution to account for the uneven surfaces you detect with the base of your foot[3]. From foot to eye to ear to proprioception, the efficient integration of the senses in the brain is essential for effectively guiding action in the world[4–6]. However, the refinement of the senses occurs gradually across development, and it is not until later childhood that efficient sensory integration emerges[7,8]. Here we ask whether the development of multisensory processing is mapped to sensorimotor abilities across childhood (see Gori et al.[9] for review), or whether these abilities develop independently[10–12] with a late emergence of these cross modal interactions due to learning or maturation of the senses (e.g. Butler et al.[13] and Wallace et al.[14]) across the lifespan.

One common way to assess the efficiency of sensory integration across development is through audio-visual temporal perception[15–17] and, more specifically, by measuring the time window during which inputs from multiple senses are combined[18–20]. This window is known as the Temporal Window of Integration (TWI). Several methods can be used to measure the TWI, the majority relying on auditory and visual stimuli. Classic measures include temporal order judgments[21,22], simultaneity judgments[23,24], and perceptual illusions such as the Sound-Induced Flash Illusion (SIFI)[25] (for reviews see Hirst et al.[26] and Keil[27]). The SIFI occurs when a single visual stimulus (a flash) presented alongside two auditory stimuli (beeps) results in the false perception of two visual flashes. Critically, when the second beep is offset in time from the first beep and the simultaneous flash stimulus (i.e., when Stimulus Onset Asynchrony (SOA) is increased) susceptibility to the illusion typically decreases. As such, the time-window over which the SIFI is induced can be used as an index of the width of the

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TWI. In line with the relationship between the SIFI and the TWI, it has been shown that training on the SIFI can result in improved performance on temporal order judgement tasks[28] as well as vice versa[29].

Most of the pioneering work developing paradigms to assess the TWI focus on audition and vision, and an interesting question is whether these audiovisual paradigms provide insight into mechanisms shared with other sensory or sensorimotor systems. Of relevance to the current study, research has found consistent relationships between audiovisual integration and balance and motor control[30] although to date most of this evidence is based on studies with older adult participants (e.g.[31] and[32]). For example, in a large-scale population study of over 4000 older adults, The Irish Longitudinal Study on Ageing (TILDA), poor audiovisual integration, measured as sustained susceptibility to the SIFI at longer SOAs was found to predict increased risk of falls over time[33,34], correlate with slower gait speed[35] and longer sit-to-stand times[36]. In a different study, Stapleton et al.[37] found that standing posture and greater postural sway were associated with greater susceptibility to the SIFI, supporting the idea that susceptibility to the SIFI might indicate a shared multisensory integration mechanism utilised in postural control. Further evidence for this comes from studies showing that explicitly training and improving balance in turn manifests reduced susceptibility to the SIFI at longer SOAs[38]. Together, these findings underscore a potential relationship between balance, postural control, and audiovisual integration in the SIFI paradigm. This further aligns with evidence for a link between visuo-somatosensory integration and falls[39]. However, despite this growing evidence, there remains a notable gap in understanding whether these associations emerge in late adulthood, or if they can be observed earlier in development, during childhood.

In addition to balance and postural control, other evidence suggests age-related links between simple motor tasks and audiovisual integration[9,40,41]. In particular, susceptibility to the SIFI has been linked to the speed of responses in a purely visual Choice Response Time (CRT) tasks in older adults. Specifically, Hirst et al.[42] found that faster CRT responses were associated with reduced SIFI susceptibility at longer stimulus onset asynchronies in older adults, which was a surprising result given that the response task involved only visual stimuli. It is well known that multisensory stimuli can facilitate simple response times, as demonstrated by the classic Redundant Signals Effect[43]. Moreover, efficient performance on such unimodal tasks also relies on rapid sensory encoding, decision-making, visuomotor transformation, and the coordination of perception and action. Therefore, associations between SIFI performance and simple visual response tasks may reflect broader aspects of perceptual–motor integration rather than multisensory facilitation per se. An additional goal of the current study was to investigate whether a similar relationship between simple visuomotor tasks and susceptibility to the SIFI exists in childhood.

It is understood that during development multiple sensory systems interact and support one another, and the capacity for the senses to support each other is an important part of childhood sensory development[9]. Using a simultaneity judgement paradigm, Noel et al.[44] demonstrated a surprisingly protracted development of the TWI, illustrating that it does not reach maturity until adolescence. This maturation of multisensory integration processes has also been reflected in studies using the SIFI. The SIFI paradigm is a useful tool for studying developmental change in multisensory integration because it can be administered relatively quickly and with simple task instructions ("Did you see one or two flashes?"). In general, studies show that SIFI susceptibility overall decreases with development between the ages of 4 and 11[15,45,46], suggesting stronger audio-visual integration in later childhood. However, other studies have reported contrasting results, including fewer illusions in children[47] and no age differences[48]. Reported increases in childhood illusion susceptibility might be reflective of the reported narrowing of the TWI[44] but also changes in sensory dominance and weighting, whereby younger children appear more influenced by auditory information[45,49,50]. Manipulating the SOA in the SIFI task may be particularly relevant both for disentangling mixed developmental effects but also understanding what mechanism is being measured by the paradigm. The duration of the SOA that elicits the illusion can also reveal important changes in the temporal dynamics of multisensory integration. Specifically, the time-window over which the illusion occurs can allow inference regarding the TWI. For example, although Stevenson et al.[51] reported reduced overall SIFI illusions in Autism Spectrum Disorder (ASD), Foss-Feig et al.[52] reported that children with ASD manifested a wider TWI when assessed with the SIFI in which SOA was manipulated. As such, the manipulation of SOA can reveal different interpretations on the maturation of multisensory integration in development.

One study that manipulated SOA in the SIFI with children also explored the impact of exercise on multisensory integration[53] (using SOAs 70, 110, 150 and 230 ms). In that study, 51 children aged 6–8 years were assigned to one of three groups: open-skill exercise (e.g., basketball, soccer, or tennis), closed-skill exercise (e.g., running or rope skipping), or a control group (sedentary classroom activity). Analyses using signal detection theory revealed a significant effect of group and SOA on perceptual sensitivity specifically (i.e. the ability to correctly identify the number of flashes). Notably, sensitivity was lowest at the 110 ms SOA (i.e. greater illusions) compared with both shorter (70 ms) and longer (230 ms) intervals, in line with the TWI, reflecting both the expected reduction in illusion perception at longer SOAs but also a reduction in illusory responses at shorter SOAs, consistent with relatively lower auditory temporal sensitivity. Further to this, both exercise groups (open and closed skill) showed improved sensitivity (reduced illusion perception) post-exercise, unlike the control group. The O'Brien et al. study therefore provides preliminary evidence that general motor activity (exercise) may enhance multisensory perceptual sensitivity in children. This, in part, supports the rationale of the current study, which further investigates links between visuomotor skill (e.g., target-hitting speed and balance) and multisensory integration (SIFI) across childhood development.

Existing studies of postural sway in childhood suggest that postural stability may emerge by the age of 6 years[54], and continue to develop until the age of 12 years[55]. In a review of postural sway in children, Verbecque et al.[56] reported children show more sway with eyes closed versus eyes open and that postural sway decreases with age, although the literature appears conflicting on the (non)linearity of its development. Furthermore, Verbecque et al. highlight that studies comparing 'eyes open' versus 'eyes closed' conditions in children have not consistently compared the same conditions (e.g. 'eyes closed' only or 'eyes open' versus 'eyes closed'), as such it remains difficult to interpret the effect of vision on balance across development.

Effective balance and motor control is scaffolded by multisensory processes including integration and reweighting, and the effective use of multisensory inputs to improve balance may emerge in later childhood. For example, Bair et al.[57] exposed children aged 4–11 to small-amplitude visual and somatosensory movements to examine their effects on postural sway. While intra-modal reweighting (use of single modality to improve stance) was seen in children as young as four, only older children showed inter-modal reweighting (using multiple modalities to improve stance), suggesting that by age 10, children begin integrating multiple sensory inputs for balance and postural control. Similarly, Polastri et al.[58], assessed postural sway in children in a moving room paradigm, wherein participants must adapt to movements in the visual environment to facilitate postural control. They found that children as young as four were able to down-weight visual information to facilitate balance, the magnitude of this recalibration was greater in 12 year olds and adults, suggesting that multisensory recalibration for postural control is a process that doesn't reach maturity until later childhood. More recently, Cheung & Schmuckler[59] showed a multisensory integration advantage of haptic support and visual input (eyes open vs closed) for postural control in children aged 6–11 compared with children aged 3–6 years, showing that balance benefits from multiple sensory inputs more across development. However, what remains less clear is whether the TWI is associated with balance control in childhood.

Processing speed to simple visuomotor response tasks is known to improve markedly across childhood and is widely considered to index general maturation of neural efficiency supporting multiple cognitive functions, including language outcomes in the early school years[60]. Children's response times decrease progressively with age, with the steepest improvements occurring in early childhood and levelling off into adolescence, consistent with the view that these simple response time tasks capture a domain-general component of neural development rather than task-specific skill[61]. Importantly, developmental improvements in response time are not limited to faster motor execution but also reflect increasing ability to anticipate predictable events and development of sensorimotor timing mechanisms. By approximately 7 to 8 years of age, children show more efficient anticipatory responding when stimulus timing is predictable[62], indicating maturation of temporal prediction and sensorimotor timing mechanisms that support coordinated action (e.g., setting a pace when running). Because multisensory integration tasks such as the SIFI rely on precise temporal processing (i.e. the ability to integrate information within narrow temporal windows) individual differences in temporal prediction and sensorimotor timing may plausibly relate to performance on such multisensory measures. To our knowledge, however, this potential relationship between predictable visuomotor response performance and SIFI susceptibility has not yet been examined.

The main objectives of the current study were therefore two-fold. First we aimed to examine developmental change in multisensory integration alongside simple measures of balance and visuomotor skill. Second, we aimed to explore if relationships exist between these measures in childhood. This second aim was inspired primarily by relationships that have been observed in older adult cohorts, leaving the question as to whether these relationships exist earlier in life.

Our first set of questions concerned developmental change in each effect independently:

Hypothesis 1 (H1): Older children should use multisensory information more for balance, and be able to balance overall for longer.
Hypothesis 2 (H2): Older children should hit more targets in 2 min than younger children.
Hypothesis 3 (H3): Older children should have more "precise" integration in the SIFI. That is, older children should be less susceptible to the Sound Induced Flash Illusion at longer SOAs, compared with younger children.

Our second set of questions concerned associations between the Sound Induced Flash illusion and balance, and the Sound Induced Flash Illusion and sensorimotor responses. Because direct evidence in children is sparse, our hypotheses were guided by findings in older adults, where a broader temporal window of integration has been linked to poorer postural stability and motor outcomes. We predicted that more efficient temporal integration, reflected in reduced SIFI susceptibility at longer SOAs, would be associated with better balance and more effective visuomotor responding:

Hypothesis 4 (H4): Those with more "precise" integration (less susceptibility to the SIFI at longer SOAs) should have longer balance times, and use vision more for balance (i.e. have a larger eyes open versus eyes closed difference).
Hypothesis 5 (H5): Those with more "precise" integration (less susceptibility to the SIFI at longer SOAs) should respond to more targets in the space of 2 min.

Methods

The study design was reviewed and approved by Trinity College Ethics committee (Approval number: SPREC062019-0) and conducted in accordance with the Declaration of Helsinki. Informed consent was provided by the parent and/or legal guardian of children participating, and assent was provided by participants themselves.

Participants

Participants were initially recruited through the University of Nottingham (Summer Scientist Online event). During this event, links to studies were posted on a custom-built event website. Participants received stars for taking part in studies, and these stars allowed children to achieve places on age-group specific leader-boards on the website. To achieve the required sample sizes, this data collection was followed up with in-person testing. We hold testing context (Summer Scientist vs. In Person data collection) as a controlled factor throughout our analyses. Figure 1 illustrates the age distribution of our full sample, which included 118 participants (aged 4–17 years, M = 8.3, SD = 2.6). The sample was 58.5% male and 41.5% female, 46.6% of participants were collected from the SSW dataset. Note that for our analysis of SIFI, we applied additional exclusion criteria which resulted in a final sample of 94 (see Analysis and Results section for full details).

Sample sizes were initially planned based on an a priori simulation-based power analysis for linear mixed-effects models with participants divided into age groups. After review, our final analysis deviated from the planned approach: age was treated as a continuous variable, and generalized linear mixed models with a binomial link were used where appropriate. We therefore conducted a simulation-based sensitivity analysis to assess the minimal detectable effect size for the age × SOA interaction in the final generalized linear mixed model, given our sample size of 94 participants.

In the simulations, each participant contributed repeated binary-outcome trials at three SOA levels (70, 150, and 230 ms), with participant-level random intercepts. Accuracy was generated from a logistic model including fixed effects of age, SOA, and their interaction. Interaction effect sizes were varied on the logit scale from 0 to 1 in steps of 0.1. For each effect size, 1,000 datasets were simulated and analysed using likelihood-ratio tests comparing models with and without the age × SOA interaction. Power was estimated as the proportion of converged models yielding a significant interaction ($\alpha = 0.05$).

This analysis indicated that an interaction effect of approximately $\beta = 0.3$ (a small to moderate effect size) on the logit scale could be detected with 80% power (estimated power = 0.80), given the final sample size.

Procedure

The task was developed in PsychoPy version 2020.1[63] and delivered through PsychoJS (version 2021.1) on pavlovia.org. Participants took part in three tasks (Fig. 2); a balance task ("The floor is lava"), a Sound Induced Flash Illusion (SIFI) task ("Calling ground control") and a timed response task ("Asteroid blast") in a sequential order. All tasks were gamified to maintain participant engagement. The majority of participants used a laptop/computer with a mouse response to perform tasks (n = 105) however a smaller number of participants recruited through Summer Scientist Week reported using a Tablet (n = 7) or phone (n = 6). At the start of the three tasks participants watched a video of the researcher explaining the instructions of all the tasks. At the start of each subtask, participants were then reminded of the instructions through onscreen text. Before starting the task a

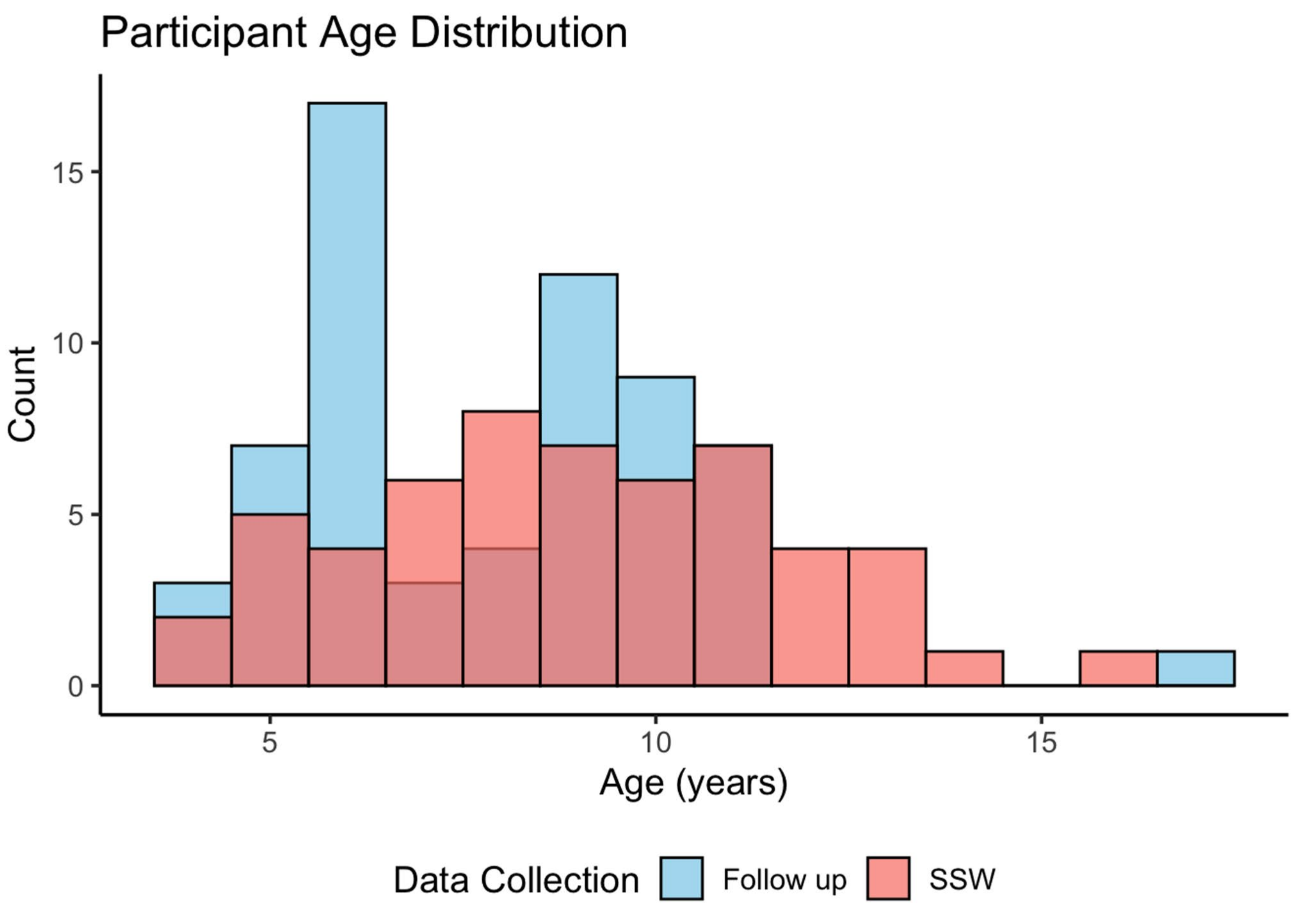

Fig. 1. Distribution of participant ages. Histogram shows the number of participants at each age, with colors indicating data collection type: Follow up and summer scientist week (SSW). Bin width is 1 year.

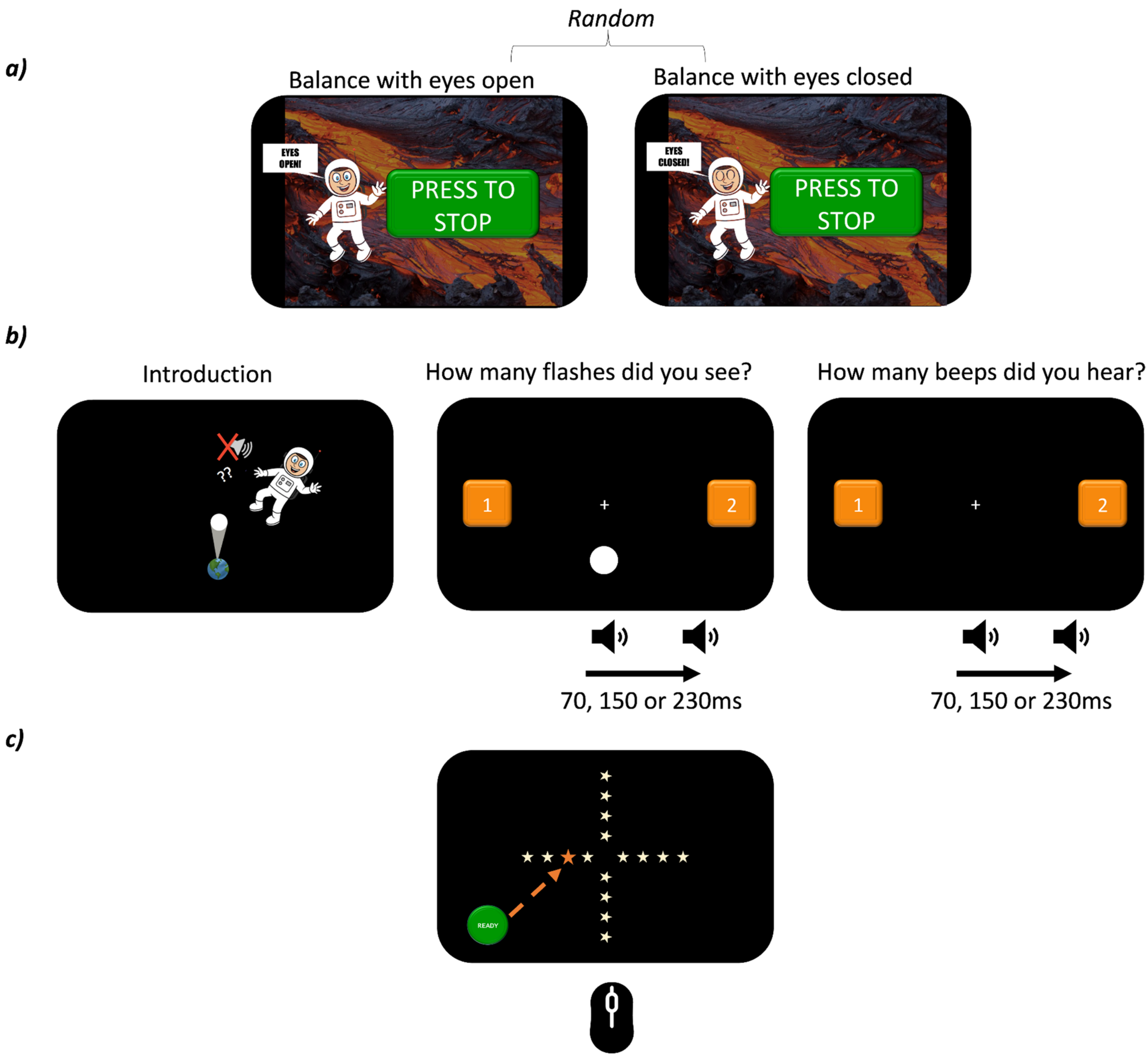

Fig. 2. Schematic illustration of each subtask. (**a**) In the balance task participants were first asked to identify which foot they would use to kick a ball, this was used as the dominant foot for the balance task. Participants were then given a max of 2 min to balance on their dominant foot with either their eyes open, or closed (in a random order across participants). (**b**) In the sound induced flash illusion task, participants were told to imagine they were decoding a "secret message" from ground control (left) in the main task (right) they were then presented with a flash or pair of flashes paired with either the same number or a different number of beeps, following this, they were presented with a block of unimodal trials in which they reported how many beeps they heard. (**c**) In the motor response task, participants were asked to first click a green "ready" button, which would immediately initiate the appearance of a star. They were asked to touch or click the star as fast as possible and to click as many stars as possible in 2 min. Targets could appear at one of 16 locations (illustrated by the light yellow dots) but only one target was shown on screen at once.

series of questions were asked about the child's participation in activities such as individual and team sport, music, dance and video gaming (in Summer Scientist Week these questions were asked by the Parent/Guardian, for in person testing the researcher asked these questions). This was to support the exploratory analyses outlined in Supplementary material Sect. 3.

Balance task

In the balance task participants were instructed to stand on their dominant leg for a maximum of 2 min, once with their eyes open and once with their eyes closed. Before the task participants were asked which leg they would use to kick a ball, and that was identified as the dominant leg. The order that the task was completed in (eyes closed or eyes open first) was assigned randomly for each participant. Participants were required to have a parent or guardian present to complete this task and control the onscreen timer (for in person testing the researcher controlled this directly).

To start the task, participants viewed an onscreen "start" button, which could be selected. Once the start button had been clicked, a 5 s countdown timer was presented onscreen. On countdown completion, participants were cued to begin to balance on their dominant foot (an auditory cue "balance" paired with an image of an astronaut balanced on the selected leg). At this point, participants viewed a timer presented onscreen and were presented with a continuous lava sound effect. They were instructed that if their other foot touched the floor they should stop the timer by selecting the onscreen "stop" button as soon as possible. If two minutes passed before the participant lost balance, the trial ended and a maximum of 2 min was recorded.

Sound-induced flash illusion (SIFI) task

In the SIFI task participants were first presented with one or two visual flashes in the presence of one, two or no auditory beeps. Participants were asked to report how many visual flashes they saw, ignoring the auditory beeps. Responses were made by selecting one of two onscreen buttons (the number 1 on the left side of the screen and the number 2 on the right side of the screen).

All visual stimuli were presented on a black background and the size of visual stimuli were all proportional to the browser window size (where 1 unit of "height" represents the full height of the viewing window). A white fixation cross (0.02 height units) was presented in the centre of the screen on which participants were instructed to fixate. A white disc (0.1 height units in diameter), representing the 'flash' was presented below the point of fixation (-0.3 height units). Auditory stimuli were brief 10 ms, ramped, 3500 Hz tones created via audacity).

Across trials we refer to conditions in the following format, 1F1B where "F" corresponds to "Flashes" and "B" corresponds to "Beeps" (therefore the "1F1B" condition would indicate a trial where one flash was paired with one beep). For conditions in which 2 (beep or flash) stimuli are presented we also refer to the Stimulus Onset Asynchrony (SOA) between stimuli in milliseconds.

Participants first completed a brief practice block of 8 trials (1F1B, 2F2B (230 ms), 1F0B, 2F0B (70 ms), 1F2B (+ 70 ms), 1F2B (– 70 ms), 1F2B (+ 230 ms), 1F2B (– 230 ms)), in a random order. They then completed 54 main trials, comprised of 14 trial types, each repeated 3 times in a random order (1F1B, 2F2B (70 ms), 2F2B (150 ms), 2F2B (230 ms), 1F0B, 2F0B (70 ms), 2F0B (150 ms), 2F0B (230 ms), 1F2B (+ 70 ms), 1F2B (+ 150 ms), 1F2B (+ 230 ms), 1F2B (– 70 ms), 1F2B (– 150 ms), 1F2B (– 230 ms)). Of note, a comprehensive study of stimulus timing in online/web browser contexts estimated that whilst the variability of audio-visual stimulus timing was relatively low (around 3.01 ms) there was a constant lag in auditory stimulus presentation of around 65 ms (Bridges et al.[67]). For this reason, we cued auditory stimuli to present 65 ms in advance of desired stimulus timing, thus aiming to achieve better synchronicity with visual stimuli.

Following this block participants were asked "Which of these did you do more?" for which they could select one of three options; "I listened to the beeps", "I watched the flashes" or "I could hear the beeps but I concentrated on the flashes"—this question was used to test that participants had understood the task and was used as a criterion for inclusion in analyses of SIFI data. Participants were then asked "How easy did you find it to count the flashes and ignore the beeps?" for which they responded on a 5 point scale; "very hard", "quite hard", "not easy or hard", "quite easy" or "very easy" (for these data see Supplementary material Sect. 4).

Following the "focus visual" block of trials and the SIFI questions, a second block was presented in which participants were asked to judge how many auditory beeps they heard. This block was presented as a control condition to ensure that participants could hear and correctly identify auditory stimuli in the absence of visual stimuli, and performance on this block was applied as an additional exclusion criteria for analysis of SIFI performance. In this block, trials from 4 conditions were presented 3 times each: in all conditions beeps were presented alone with no visual flashes (0F1B, 0F2B (70 ms), 0F2B (150 ms), 0F2B (230 ms)).

Motor response task

The motor response task was delivered to assess basic motor skills. Our task was adapted from previous studies which used tablet-based assessments to successfully measure motor responses in children[64–66]. On each trial the participant selected a "start" button in the lower left portion of the screen, and a target (a star) was then immediately presented at one of 16 locations presented in a cross formation centred on the screen. The presentation of each target was therefore self-paced, as targets immediately followed the participants' selection of the "start" button. Participants were instructed to touch as many targets as they could within 2 min. Prior to the main task participants completed a 15 s practice trial in which they tried to hit as many targets as they could within the time limit. Due to known issues with assessing absolute response times for online tasks[67] we used the number of targets hit as the dependent variable in our analysis as opposed to response time measures themselves.

Analysis

Detailed methods and results for each stage of the analysis are described in the corresponding sections below. In brief, our analysis proceeded in four stages.

First, we assessed developmental changes in simple balance and motor performance. Specifically, we computed Pearson correlations between age and (a) balance difference scores, and (b) the number of targets hit within two minutes.

Second, we examined age-related changes in performance on the sound-induced flash illusion (SIFI) task to characterize developmental changes in multisensory integration. Prior to analyzing illusion rates and multisensory performance, we applied additional exclusion criteria: (a) participants who reported "listening" to the beeps in blocks where they were instructed to "watch" the flashes, and (b) participants with poor unimodal performance, either in the auditory block or on visual-only trials in the multisensory block at longer SOAs. We provide a thorough overview of unimodal performance in Supplementary Sect. 1.

Third, we applied signal detection theory (SDT) to further quantify developmental changes in perceptual sensitivity (d′) and response bias (c) on the multisensory trials.

Finally, to assess whether balance and motor performance were associated with multisensory integration across development, we fit the same models used to explore age-related changes in SIFI, including balance difference score/number of targets hit (in separate models), as well as their interaction with SOA, thus allowing us to identify if balance and motor responses predicted different patterns of illusion susceptibility across SOAs.

Results

Balance and motor responses

To address the extent to which each child used multisensory information for balance, we calculated a balance difference score as:

balance_difference_score = balance_time_eyes_open -balance_time_eyes_closed.

Thus, more positive scores indicate a greater use of vision to assist balance. Pearson correlations were used to assess if balance and motor responses showed linear associations with age in years. Figure 3 illustrates the change in balance difference scores and number of targets hit with increasing age.

The Pearson correlation between Balance Difference Score and Age was statistically significant ($p = < 0.001$, r = 0.37; 95% confidence intervals 0.2 to 0.52). Similarly, the Pearson correlation between number of targets hit in two minutes and Age was also statistically significant ($p = < 0.001$, r = 0.68; 95% confidence interval from 0.57 to 0.77). We interpret this as indicating a developmental change in the use of vision for balance (larger difference scores with increasing age) alongside the expected developmental change in number of targets hit in two minutes (with older children hitting more targets in the time limit).

Sound induced flash illusion

To examine age-related changes in the Sound-Induced Flash Illusion, we fitted generalized logistic mixed-effects models with a binomial logit link function to predict accuracy (proportion correct), on illusory trials (2 beep 1 flash conditions), modeled as a function of SOA, age in years (continuous), and their interaction, with testing condition (Summer Scientist Week vs. In Person follow-up) included as a covariate. All models included a

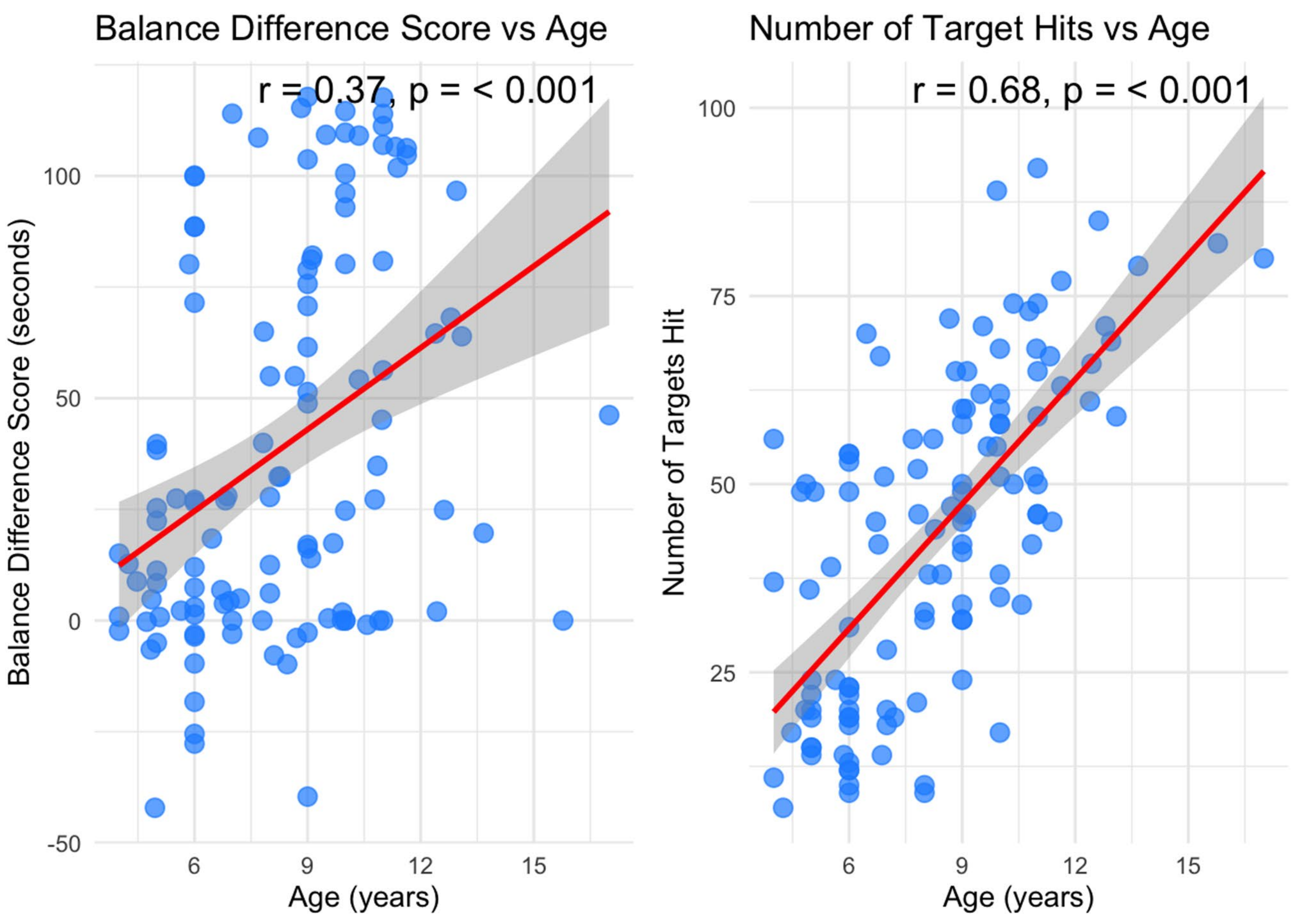

Fig. 3. Scatterplot showing the relationship between age (in years) and balance difference score in seconds (left) and age and nHits (number of targets hit in 2 min; right). A linear regression line (in red) illustrates a positive association between age and balance difference score as well as between age and and nHits, showing use of vision for balance and number of targets hits increases with age.

random intercept for participant to account for repeated measures. Models were fit using the bobyqa optimizer with an increased iteration limit (maxfun = 1×10^6) to ensure convergence. The significance of the SOA × age interaction and of the main effects of age and SOA was assessed using likelihood ratio tests, comparing the full model to reduced models with the term of interest removed.

For models exhibiting a significant interaction, simple slopes analyses were conducted to examine the effect of age at each SOA level (70, 150, and 230 ms). In addition, when a main effect of SOA was observed, pairwise comparisons of SOA levels were performed using estimated marginal means with Holm correction for multiple comparisons.

Model comparisons of the generalized mixed effects models indicated that the interaction term between SOA and Age significantly improved model fit ($\chi^2(2) = 17.9$, $p = < 0.001$). Similarly, Age ($\chi^2(1) = 13.94$, $p = < 0.001$) and SOA ($\chi^2(2) = 24.24$, $p = < 0.001$) also contributed to model fit.

Pairwise comparisons of SOA levels indicated that accuracy was highest at 230 ms, followed by 150 ms, and lowest at 70 ms. Specifically, accuracy at 150 ms was significantly lower than at 230 ms (odds ratio = 0.5, $p = < 0.001$) and accuracy at 70 ms was significantly lower than at 230 ms (odds ratio = 0.57, $p = < 0.001$). Accuracy between 70 and 150 ms did not reliably differ (odds ratio = 1.13, $p = 0.404$).

As age increased, a clear pattern emerged: accuracy improved most at the 230 ms SOA, followed by 150 ms, and least at 70 ms. Simple slopes analyses showed that age did not significantly predict accuracy at 70 ms ($\beta = 0.12$, $p = 0.108$), but significantly predicted accuracy at 150 ms ($\beta = 0.33$, $p = < 0.001$) and 230 ms ($\beta = 0.35$, $p = < 0.001$). Post-hoc comparisons confirmed that age-related slopes at 150 ms and 230 ms were significantly steeper than at 70 ms ($ps \leq 0.001$), whereas slopes at 150 ms and 230 ms did not differ ($p = 0.665$) (Fig. 4).

Signal detection theory

We implemented signal detection theory (SDT) to determine participants' ability to correctly identify the number of flashes, during two-beep trials and no beep trials. This further allowed us to assess whether the change in the proportion of illusory reports resulted from changes in perceptual sensitivity, response bias, or both.

We computed *d*′ as:

$d' = Z(\text{Hit Rate})—Z(\text{False Alarm Rate})$

Where *Hit Rate* is the rate of correctly reporting the number of flashes and *False Alarm Rate* is the rate of incorrectly reporting the number of flashes. These were calculated independently for 0 beep and 2 beep conditions (as in Rosenthal et al.[68]).

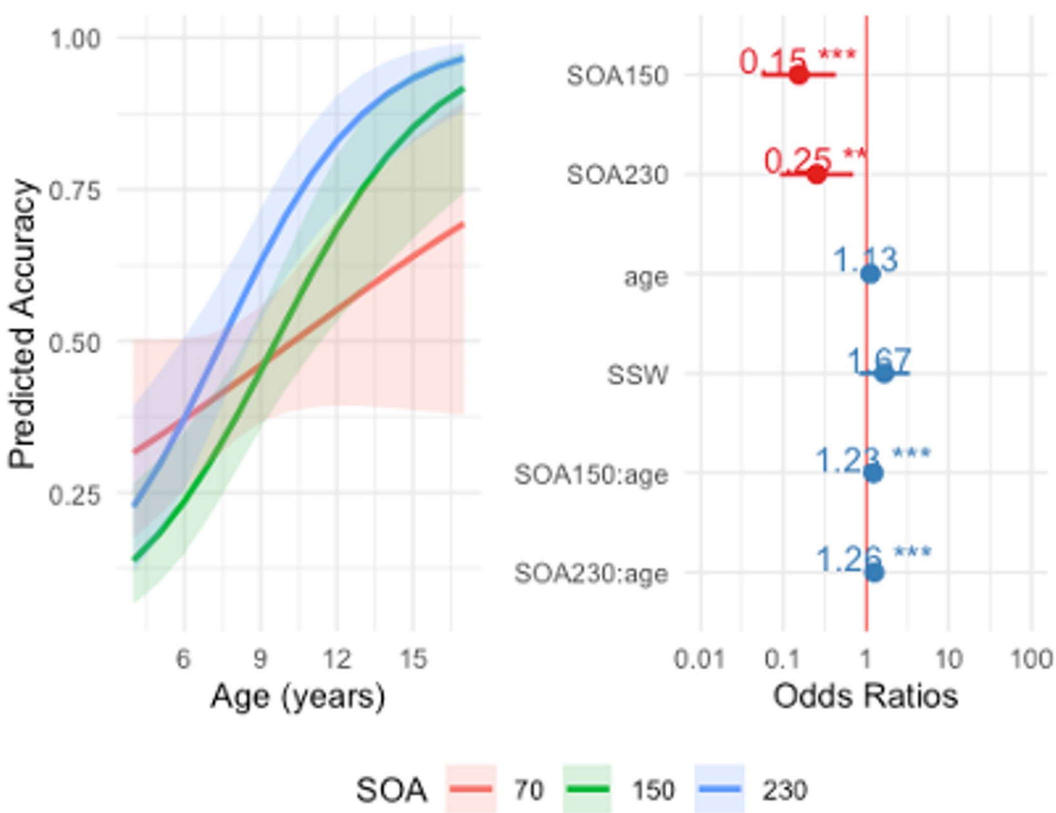

Fig. 4. Predicted accuracy and GLMM fixed effect estimates for unimodal trials. (**A**) Predicted probability of correct responses across ages for each SOA, based on estimated marginal means from the GLMM. Shaded areas indicate 95% confidence intervals. Accuracy increases with age, particularly at longer SOAs. (**B**) Fixed effect estimates from the same GLMM, including coefficients for SOA, age, and their interaction, with 95% confidence intervals and significance values indicated. The red vertical line indicates zero effect.

We computed *d'* for each beep condition as follows:

d′(2 beeps) = Z("2 flash" response on 2F2B trial)—Z("2 flash" response on 1F2B trial)

d′(0 beeps) = Z("2 flash" response on 2F0B trial)—Z("2 flash" response on 1F0B trial)

These were calculated at each SOA (70, 150, 230 ms). As the SIFI represents incorrectly reporting two flashes when one flash is presented with two beeps, illusions are expressed as lower *d′* (2 beeps) compared with *d′* (0 beeps).

Response bias (*c*) was defined as:

c = − 0.5 * [Z(Hit Rate) + Z(False Alarm Rate)]

And was therefore calculated for each beep condition as:

c(2 beeps) = − 0.5 * [Z("2 flash" response on 2F2B trial) + Z("2 flash" response on 1F2B trial)]

c(0 beeps) = − 0.5 * [Z("2 flash" response on 2F0B trial) + Z("2 flash" response on 1F0B trial)]

Response bias was also calculated independently for 2 beep and 0 beep conditions. Presenting one flash with multiple beeps is likely to increase uncertainty, which may introduce response bias towards a "2 flash" response. Signal detection theory metrics (d′ and criterion c) were computed for each participant and condition. To avoid undefined values for the Z-transformation at hit rates or false alarm rates of 0 or 1, we applied a correction by converting 1 s to 1–0.5/ntrials and 0 s to 0.5/ntrials where ntrials is the number of trials for each condition (6 trials: Each 1F2B condition was presented 3 times with an auditory lead and 3 times with a visual lead, we collapse across auditory and visual lead trials to provide 6 trials per SOA).

Two linear mixed-effects models (with restricted maximum likelihood estimation) were fitted to predict d′ and response bias respectively. Each model included fixed effects for SOA, Age (in years), their interaction, number of beeps (0 or 2), and test condition (SSW or In Person follow up), with a random intercept for participant. To assess the significance of the interaction term and each fixed effect, we then fit models without the interaction term, and then without the effect of each main effect and formally compared these models. These were performed for both d′ and response bias.

For sensitivity (d′), model comparisons indicated that there was a significant contribution of Age ($\chi^2(3) = 39.07$, $p = < 0.001$) and SOA ($\chi^2(4) = 161.45$, $p = < 0.001$) and the interaction between SOA and Age significantly improved model fit ($\chi^2 = \chi^2(2) = 16.63$, $p = < 0.001$). Simple slopes analyses for the interaction effect showed that Age did not significantly predict d′ at 70 ms ($\beta = 0.042$, $p = 0.148$), but that Age did significantly predict sensitivity at 150 ms ($\beta = 0.157$, $p = < 0.001$), and 230 ms ($\beta = 0.14$, $p = < 0.001$). The age-related slope was therefore significantly steeper at 150 ms versus 70 ms ($p = < 0.001$) and 230 ms versus 70 ms($p = 0.003$), whereas slopes at 150 ms and 230 ms did not significantly differ ($p = 0.566$).

As expected, the number of beeps significantly improved model fit ($\chi^2(1) = 136.07$, $p < 0.001$). Predicted sensitivity (d′) was higher in the zero-beep condition (predicted d′ = 1.81) than in the two-beep condition (predicted d′ = 0.99). The difference between conditions was statistically significant ($\Delta d' = 0.82$, $p < 0.001$).

For response bias, the interaction between SOA and age did not significantly improve model fit ($\chi^2(2) = 0.92$, $p = 0.630$). However, Age significantly improved model fit ($\chi^2(3) = 14.98$, $p = 0.002$); older participants were slightly less likely to report two flashes erroneously ($\beta = 0.06$, $p = < 0.001$). The main effect of SOA was also significant ($\chi^2(4) = 92.61$, $p = < 0.001$); participants were more conservative at short SOAs (70 ms, M = 0.08) and more liberal at longer SOAs (150 ms, M = − 0.35, $p = < 0.001$; 230 ms, M = − 0.3, $p = < 0.001$), indicating that they were more likely to report two flashes at longer SOAs. This shift in response bias likely reflects increased perceptual separability of the flashes at longer temporal offsets, reducing uncertainty and favouring responses consistent with the physical stimulus.There was no significant difference in response bias between 150 and 230 ms ($p = 0.286$).

The main factor of number of beeps also significantly contributed to the model of response bias ($\chi^2(1) = 224$, $p = < 0.001$). Response bias was more negative in the 2-beep condition (M = -0.51) than in the 0-beep condition (M = 0.13, $p = < 0.001$), indicating that the presence of two beeps increased the tendency to report two flashes, consistent with a bias toward perceiving multiple flashes (Fig. 5).

Are illusory responses on the SIFI related to balance and motor responses?

To assess whether balance and motor responses were associated with multisensory integration, as measured by the Sound-Induced Flash Illusion (SIFI) across development, we fit two parallel generalized logistic mixed-effects models (binomial family with logit link, using the "bobyqa" optimizer and optCtrl = list(maxfun = 2e5) to aid convergence). Both models included the same terms as our primary analysis of developmental changes in the SIFI, predicting the proportion of correct responses on illusory trials from age, SOA, and their interaction, while controlling for testing condition (In Person vs. Summer Scientist Week). Additionally, the balance model included an interaction between SOA and balance difference score, and the motor response model included an interaction between SOA and number of targets hit (nHits).

As in our previous analyses, the significance of each main effect and interaction term was assessed by comparing the full model to a reduced model excluding the effect of interest. For significant interaction terms, we conducted post hoc simple slopes analyses with Holm correction, while significant main effects were followed up with post hoc pairwise comparisons.

The results from our balance model suggested that the balance difference × SOA interaction did not significantly contribute to model fit ($\chi^2(2) = 0.42$, $p = 0.811$). Consistent with our primary analysis the Age × SOA interaction significantly improved model fit ($\chi^2(2) = 16.78$, $p < 0.001$). Similarly, the main effect of age ($\chi^2(3) = 28.89$, $p < 0.001$) and SOA were significant contributors ($\chi^2(6) = 42.56$, $p < 0.001$), however the main effect of balance difference score was not a significant contributor to model fit ($\chi^2(3) = 0.43$, $p = 0.933$).

Simple slopes analyses for the interaction effect showed that Age did not significantly predict proportion correct at 70 ms ($\beta = 0.121$, $p = 0.143$), but that Age did significantly predict responses at 150 ms ($\beta = 0.326$, $p = < 0.001$), and 230 ms ($\beta = 0.366$, $p = < 0.001$).

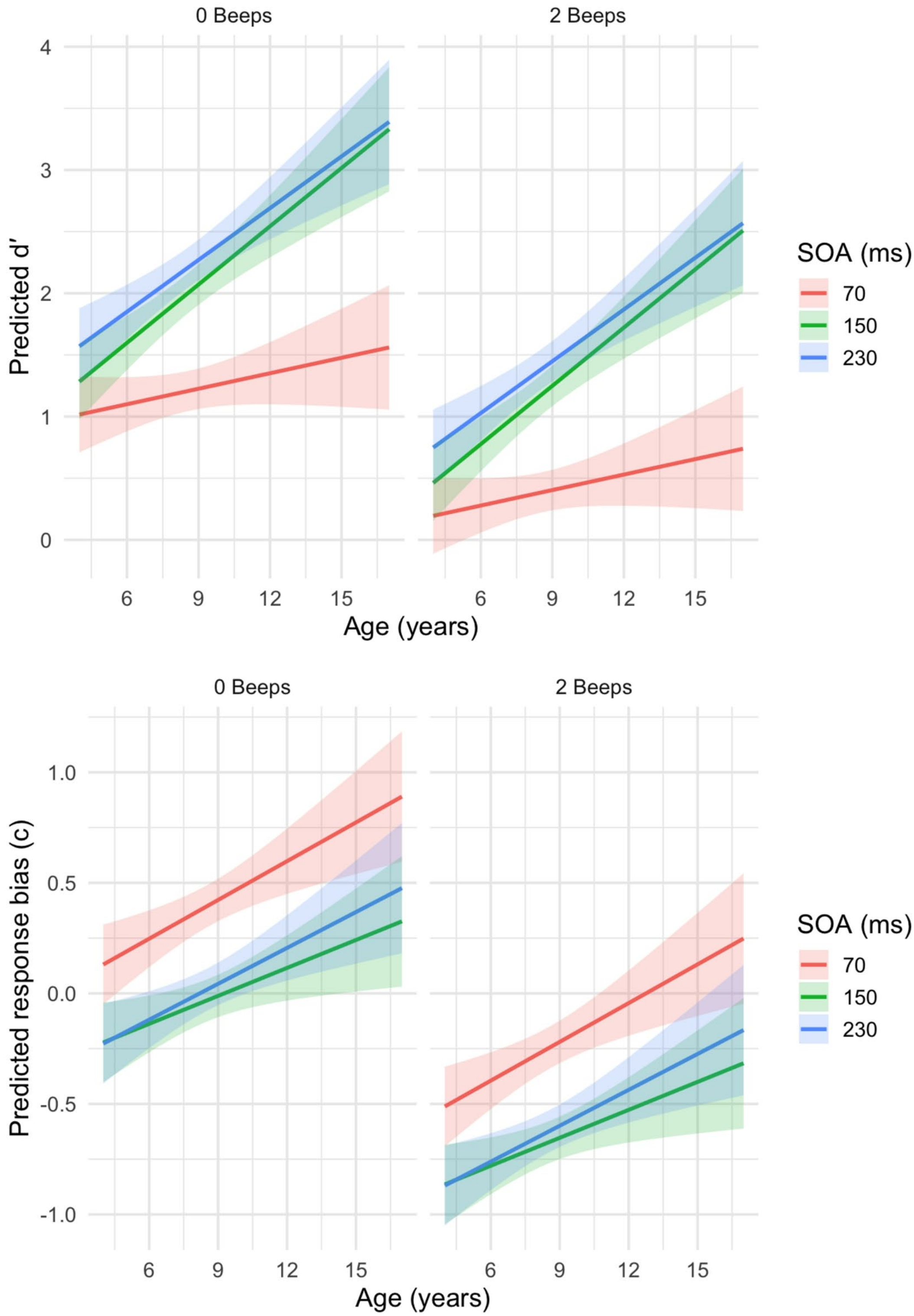

Fig. 5. Predicted sensitivity (d') and response bias (**c**) across age for different stimulus onset asynchronies (SOAs) and number of auditory beeps. Lines represent estimated marginal means from the mixed-effects model, and shaded ribbons show 95% confidence intervals. Separate panels compare trials with 0 versus 2 beeps, illustrating how age and SOA influence response bias.

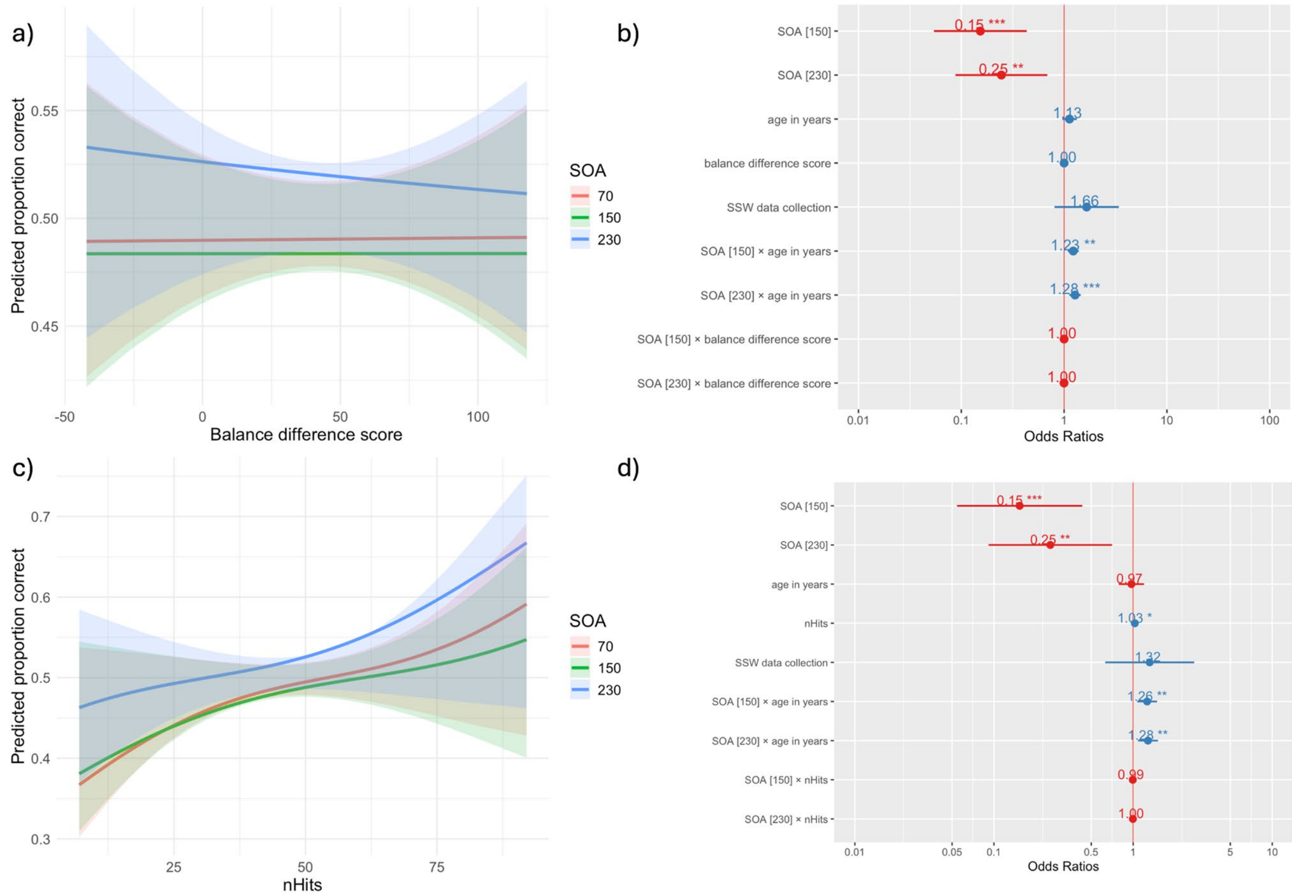

Fig. 6. (**a**) Relationship between balance difference scores and accuracy on illusory SIFI trials and (**c**) predicted proportion of correct responses as a function of balance difference score/nHits for each SOA condition. Lines represent population-level predictions from a generalized linear mixed-effects model (binomial, logit link) including both age × SOA and balance difference score/nHits × SOA interactions. Shaded ribbons indicate 95% confidence intervals. Predictions were bias-corrected to account for the nonlinear link function. (**b** and **d**) Fixed effect estimates from the generalized linear mixed-effects model (GLMM) examining the interaction between stimulus onset asynchrony (SOA) and continuous age (in years), as well as SOA and balance difference score/nHits, on SIFI accuracy (proportion correct) in illusory trials. Error bars represent 95% confidence intervals, and the red vertical line denotes the null effect (odds ratio = 1).

The age-related slope was significantly steeper at 150 ms versus 70 ms ($p = 0.002$) and 230 ms versus 70 ms ($p = < 0.001$), whereas slopes at 150 ms and 230 ms did not significantly differ ($p = 0.543$).

For our analysis of motor responses (number of targets hit in two minutes, nHits) and SIFI, the Age × SOA interaction significantly improved model fit ($\chi^2(2) = 10.58$, $p = 0.005$) however the nHits × SOA interaction did not ($\chi^2(2) = 0.24$, $p = 0.889$). Age ($\chi^2(3) = 12.35$, $p = 0.006$) and SOA ($\chi^2(6) = 42.29, < 0.001$) were significant, whereas nHits alone ($\chi^2(3) = 4.19$, $p = 0.241$) was not.

Simple slopes analyses for the interaction effect in the nHits model showed that Age did not significantly predict proportion correct at 70 ms ($\beta = -\ 0.028$, $p = 0.793$) or 150 ms ($\beta = 0.204$, $p = 0.058$), but Age did significantly predict proportion correct at 230 ms ($\beta = 0.218$, $p = 0.043$).

The age-related slope was significantly steeper at 150 ms versus 70 ms ($p = 0.012$) and 230 ms versus 70 ms ($p = 0.011$), whereas slopes at 150 ms and 230 ms did not significantly differ ($p = 0.875$) (Fig. 6).

Discussion

In this study, we aimed to build on existing research using the Sound-Induced Flash Illusion (SIFI) to investigate the development of multisensory integration. Specifically, we examined the development of balance, motor responses, and SIFI performance across childhood to identify if the relationships between these metrics observed in ageing could be detected in childhood. We first assessed developmental changes in each of these processes independently. We then extended this analysis to explore whether use of vision for balance (as indexed by the balance difference score) and motor performance (measured by the number of targets hit in 2 min) predicted susceptibility to the SIFI across a range of stimulus onset asynchronies (SOA), to determine whether balance and motor control are related to the TWI in multisensory integration throughout childhood development.

As predicted, we found that all three measured processes manifested developmental change. There was a significant increase in the number of targets hit in 2 min with increasing age. Furthermore, older children were more likely to use vision for balance (thus manifesting larger balance difference scores) compared with the youngest age group. This is consistent with existing literature indicating that older children are more likely to integrate vision to assist balance[59] and findings that older children are more likely to exhibit inter-modal reweighting in balance control[57]. Interestingly, this also indicates that our paradigm can provide an easy to implement measure of balance to be conducted through remote data collection.

Our SIFI data build upon developmental literature utilising SOA as a factor with the aim of better understanding the temporal dynamics of multisensory integration. To date, most developmental studies have explored illusion rate overall, rather than examining illusion rate across a range of SOAs. We found a significant interaction between age group and SOA, such that accuracy at longer SOAs showed improvement with age. We interpret this to reflect a refinement in the TWI across development. We also observed that this emerged primarily due to changes in perceptual sensitivity (*d'*) rather than response bias. Of note, we actually observed that, in younger children, illusions peaked (i.e. accuracy was lower) at 150 ms compared with 70 ms and 230 ms. Although this contrasts with what has been demonstrated in adults' performance to infer a temporal window of integration[25] this aligns with what has been reported in previous studies with children[53]. Given that children showed high accuracy for detecting two beeps at all SOAs when presented unimodally, this cannot be explained by a low auditory temporal sensitivity at 70 ms. Rather, it is possible that low sensitivity to two flashes presented at 70 ms SOA may make a "1 flash" response more likely at this SOA. Nevertheless, the reduction in illusions (improved accuracy) between 150 and 230 ms, despite high accuracy for detecting two unimodal flashes at both of these SOAs, is consistent with the expected reduction in illusion rate at longer SOAs.

Based on existing literature demonstrating associations between balance and SIFI susceptibility in younger and older adulthood[34–37,69], we aimed to determine whether similar relationships exist during childhood. However, we did not find convincing evidence for an association between our measures of balance or motor control and SIFI illusion susceptibility. The interaction between balance difference scores and SOA in predicting illusion susceptibility failed to reach significance. Similarly, the number of target hits in our motor task did not significantly interact with SOA. Although we observed a small, non-significant relationship between the number of target hits and overall SIFI accuracy—where more hits were associated with higher accuracy and fewer illusions—this may be attributable to shared variance with age, as older children generally achieved a greater number of target hits.

Before concluding that there is no relationship between balance, motor responses, and measures of audiovisual integration in childhood, it is important to consider possible explanations for this lack of association. One possibility is that our measures of balance and motor responses were not sensitive to the specific processes that underlie multisensory integration. In other words, the absence of a relationship in our data may reflect task specificity. Because our initial data collection began during the COVID-19 pandemic, we selected tasks that could be administered remotely without the need for specialized hardware. As a result, we employed a relatively crude metric of balance—namely, the duration participants could stand on one leg with eyes open versus closed. It is possible that this measure did not capture the specific dimensions of balance that are most relevant to multisensory integration. There is a breadth of information available through examining postural sway in childhood (for a review see[56]) and sway has been associated with SIFI perception in studies with adults[37]. As such, an interesting direction for future research would be to examine if postural sway metrics appear tied to measures of the TWI, such as SIFI, in childhood. Similarly, our motor response task prioritized speed (i.e., number of targets hit in two minutes) rather than precision (e.g., accuracy in hitting a small or moving target). It is therefore possible that the use of alternative tasks—particularly those assessing different facets of balance or motor control—might reveal relationships with SIFI susceptibility that were not observable in our study.

Further to this, in our design, children completed the SIFI, balance and motor measures independently, as opposed to a design where audiovisual integration is assessed during the act of balance and movement. Experimental studies with adults have examined SIFI susceptibility during the act of standing versus sitting, whilst also assessing postural sway[37,70]. Furthermore, an interesting strand of research has illustrated that contrast sensitivity[70] and audiovisual synchrony[30] appear modulated during the walking. As such, it is possible that a similar, concurrent, design in children might reveal similar links between audiovisual integration and balance and motor responses. Additionally, studies in older adults have employed longitudinal assessments, such as longitudinal self-reported fall data[33,34]. One avenue for future research might be to assess if links between audiovisual integration and balance and motor responses emerge over a longitudinal time course.

The current study highlights important future directions for assessing the relationships between audiovisual integration, balance and motor control. However, it is possible, given our data, that associations between balance, motor function, and multisensory integration simply emerge later in development and are genuinely not present—or not detectable—during childhood. If so, it raises an important question: do changes in the susceptibility to audio-visual illusions precede declines in balance and motor control, or is it a consequence of them? Given that both balance training[38] and exercise[53] have been shown to reduce susceptibility to the SIFI at longer SOAs, one might hypothesize that multisensory integration—as assessed by the SIFI—improves as a *result* of enhanced balance and visuomotor skill, rather than driving those changes. Given that use of vision to improve balance duration emerged in our older child participants, it is possible that the integration mechanisms shared between audiovisual perception and balance control are more likely to be detected at later stages of development and adulthood, as use of multiple sensory inputs to control posture develop.

Although not the primary focus of this study, we conducted several exploratory analyses examining the relationship between children's self-reported daily activities and audiovisual integration performance (see Supplementary Sect. **3**). Children were asked whether they participated in individual or team sports, formal music training, video gaming, or formal dance training. Most of these factors were not significantly associated with SIFI susceptibility. However, we observed a small but statistically significant effect of formal dance training (yes/no), such that children with dance training were less susceptible to the illusion—particularly at the longest SOAs. This finding aligns with prior research in adults, which suggests that dance is associated with distinct audiovisual integration profiles[71,72] particularly in the context of rhythmic movement[73]. Interestingly, Nguyen et al. reported less influence of distracting sounds in dancers relative to musicians, which may help explain why children with dance training are less susceptible to the SIFI (which is driven by sound). We did not observe an effect of individual sports participation (e.g., football) unlike previous findings on studies with adults[74]. However it is worth noting that Quinn et al. reported effects specific to goalkeepers rather than outfield players, and our measure may have lacked this specificity. Similarly, although previous work in adults has linked video game experience to altered SIFI susceptibility[75], as well as improved unisensory visual temporal resolution[76], we found no such effect in children. This may reflect developmental differences or the lack of detailed information about the type of games played (e.g. First Person Shooter games). Nonetheless, the observed effect of formal dance training on SIFI perception represents a novel and potentially meaningful finding, meriting further investigation in future studies.

Another interesting finding from our exploratory analyses relates to children's self-reported ease of the SIFI task—specifically, how easy they found it to focus on the flashes and ignore the beeps. A growing body of research on metacognitive awareness has shown that, in adults, confidence ratings provided on a trial-by-trial basis during the SIFI task are related to both accuracy and illusion susceptibility. Specifically, more confident judgments tend to be associated with more accurate (i.e., non-illusory) percepts[77]. Although we asked about task difficulty only once, at the end of the task rather than on a trial-by-trial basis, our exploratory findings suggest a similar pattern in children (see Supplementary Sect. 4). This provides a novel indication that metacognitive awareness may begin to develop in childhood and highlights the potential value of further research examining the relationship between metacognition and multisensory illusion perception in this age group.

Conclusions

In this study, we investigated whether multisensory integration—as indexed by susceptibility to the Sound-Induced Flash Illusion (SIFI) at shorter versus longer SOAs- is associated with balance and motor responses during childhood. While we observed clear age-related improvements across all three domains (multisensory integration, balance, and visuomotor skill), we found no compelling evidence of a direct relationship between them. Specifically, neither the number of targets hit in two minutes nor the balance difference score (eyes open vs. closed) significantly predicted susceptibility to the SIFI, nor did either interact with stimulus onset asynchrony (SOA) to influence illusion perception. These findings suggest that, within the parameters of our task, balance and sensorimotor performance are not closely linked to susceptibility to audiovisual temporal illusions in children. Further research using alternative, possibly more sensitive, measures may help clarify whether such relationships emerge at different stages of development or under different testing conditions. Although not central to the present investigation, exploratory analyses revealed tentative associations between SIFI susceptibility and both formal dance training and self-reported task difficulty, highlighting additional factors that may shape multisensory processing and warrant future investigation.

Data availability

The data and materials associated with this study are openly available. The full dataset, analysis scripts, and supplementary materials can be accessed via the OSF project page: https://osf.io/q5zgt/?view_only=75d649f38f824951a4416218005c7df4. The experimental task ("Space Raiders 2") is available on Pavlovia: https://gitlab.pavlovia.org/lpxrh6/space_raiders_2.

Received: 28 July 2025; Accepted: 12 March 2026
Published online: 25 March 2026

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Acknowledgements
This research was supported by funding from Science Foundation Ireland to FNN under grant number 19/FFP/6812.

Author contributions
RH, FNN and AS designed and planned the study. EM was responsible for follow up data collection and assistance with analyses. RH analysed the data and prepared the manuscript for publication. All authors reviewed and approved the final manuscript.

Funding
This research was supported by funding from Science Foundation Ireland to FNN under grant number 19/FFP/6812.

Competing interests
The authors declare no competing interests.

Additional information
Supplementary Information The online version contains supplementary material available at https://doi.org/10.1038/s41598-026-44660-9.

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