Published in final edited form as:

Neurosci Lett. 2010 October 8; 483(1): 36–40. doi:10.1016/j.neulet.2010.07.056.

Improvements in proprioceptive functioning influence multisensory-motor integration in 7- to 13-year-old children

Bradley R. King¹, Melissa M. Pangelinan^{1,2}, Florian A. Kagerer^{3,4}, and Jane E. Clark^{1,2}

¹Cognitive Motor Neuroscience Laboratory, Department of Kinesiology, University of Maryland, College Park, Maryland ²Graduate Program in Neuroscience and Cognitive Science, University of Maryland, College Park, Maryland ³Department of Kinesiology, Michigan State University, East Lansing, Michigan ⁴Neuroscience Program, Michigan State University, East Lansing, Michigan

Abstract

Accurate and efficient sensorimotor behavior depends on precise localization of the body in space, which may be estimated using multiple sensory modalities (i.e., vision and proprioception). Although age-related differences in multisensory-motor integration across childhood have been previously reported, the extent to which age-related changes in *unimodal* functioning affect multisensory-motor integration is unclear. The purpose of the current study was to address this knowledge gap. Thirty-seven 7- to 13-year-old children moved their dominant hand in a target localization task to visual, proprioceptive, and concurrent visual and proprioceptive stimuli. During a subsequent experimental phase, we introduced a perturbation that placed the concurrent visual and proprioceptive stimuli in conflicting locations (incongruent condition) to determine the relative contributions of vision and proprioception to the multisensory estimate of target position. Results revealed age-related differences in the localization of incongruent stimuli in which the visual estimate of target position contributed more to the multisensory estimate in the younger children whereas the proprioceptive estimate was up-weighted in the older children. Moreover, above and beyond the effects of age, differences in proprioceptive functioning systematically influenced the relative contributions of vision and proprioception to the multisensory estimate during the incongruent trials. Specifically, *improvements* in proprioceptive functioning resulted in an *up-weighting* of proprioception, suggesting that the central nervous system of school-aged children utilizes information about unimodal functioning to integrate redundant sensorimotor inputs.

Introduction

Prior to the execution of goal-directed reaching, the central nervous system (CNS) utilizes information about the positions of both the target and the arm to generate an appropriate motor plan [4;5]. This process depends not only on the precision and accuracy of an individual sensory modality, but also on the ability to integrate information from multiple modalities (i.e., vision and proprioception) with available motor outflow (i.e., efferent copy

© 2010 Elsevier Ireland Ltd. All rights reserved.

Correspondence: Bradley R. King, Cognitive Motor Neuroscience Laboratory, Department of Kinesiology, 2351 SPH Building, University of Maryland, College Park MD 20742-2611 Telephone: 301-405-2574, Fax: 301-405-5578, bking7@umd.edu.

Publisher's Disclaimer: This is a PDF file of an unedited manuscript that has been accepted for publication. As a service to our customers we are providing this early version of the manuscript. The manuscript will undergo copyediting, typesetting, and review of the resulting proof before it is published in its final citable form. Please note that during the production process errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

of the motor command). Previous research has employed localization tasks during which participants actively moved an unseen hand to localize visual, proprioceptive, and simultaneously presented visual and proprioceptive stimuli, the latter requiring multisensory-motor integration. Thus, the accuracy and variability of such localization tasks reflect the localization of the target and the localization of the unseen moving hand. Whereas unimodal sensorimotor acuity in adults is precise and stable, developmental changes across childhood result in robust differences in the localization of unimodal stimuli [6;26]. These changes in unimodal sensorimotor acuity likely impact multisensory-motor integration. The purpose of this study was to investigate the effects of unimodal sensorimotor functioning on multisensory-motor integration in 7- to 13-year-old children.

Previous developmental research examining the localization of unimodal and bimodal stimuli demonstrated that children are consistently more accurate when moving an unseen hand to visual (V) as compared to proprioceptive (P) stimuli [16;26]. Moreover, performance during bimodal conditions (i.e., VP) is nearly identical to the visual condition, suggesting that when both sensory stimuli are available, vision is the more dominant modality [26]. Although non-monotonic age-related improvements were reported in all experimental conditions (V, P, and VP), the magnitude of the improvement in the localization of proprioceptive stimuli between 7 and 9 years of age was greater than improvement in localization of visual stimuli [26]. This result is consistent with research by Contreras-Vidal [6] who suggested that the age-related improvements in proprioceptive acuity across 6- to 10-year-old children contribute to the age-related improvements in sensorimotor performance reported in the extant literature [2;7;11;13;28].

The current experiment sought to determine how unimodal sensorimotor functioning in children impacts multisensory-motor integration and to provide insights into the underlying processes. In addition to examining localization of visual, proprioceptive, and simultaneously presented visual and proprioceptive stimuli, we introduced a spatial perturbation that placed visual and proprioceptive estimates of target position in conflict. The relative contribution of each modality was estimated based on the end-point position during these incongruent bimodal trials. It was hypothesized that unimodal localization performance would systematically impact multisensory-motor integration in 7- to 13-year-old children. More specifically, greater accuracy of unimodal localization will result in a greater contribution of that particular modality to the multisensory estimate.

Materials and methods

Thirty-seven typically-developing children (23 females; 14 males), ages 7 to 13 years, participated in the study. All participants had normal or corrected vision and were right-handed, as determined by their preferred hand used to complete everyday activities such as handwriting. To ensure typical and healthy development, the parents of the child participants completed a neurological health questionnaire to preclude any neurological deficits or developmental delay. Additionally, the children were screened with the Movement Assessment Battery for Children (MABC) [12], and were included in this study if they scored at or above the 20th percentile. All experimental procedures were approved by the Institutional Review Board at the University of Maryland, College Park. Parents or legal guardians of the participants provided informed consent prior to participation. Informed assent was obtained from the children. Upon completion of the experiment, the children received a small prize and a modest monetary compensation.

Participants were seated in a height-adjustable chair in front of a two-tiered experimental apparatus resting on a table (Figure 1A). A digitizing tablet (12"x12" WACOM InTuos™) was positioned on the bottom tier of the apparatus. The top tier supported a horizontally-

oriented flat screen monitor. Participants were informed that they would use both hands, with their pronated right hand moving a digitizing pen across the surface of the tablet, and their supinated left hand moving to positions underneath the tablet. The computer screen provided feedback of the visual targets and, when appropriate, the end-point (EP) position of the pen. Vision of the participants' hands was occluded using a black cloth secured onto the apparatus and draped comfortably around the participants' shoulders (not shown in Figure 1A). OASIS software (Kikosoftware® Nijmegen, Netherlands) was used for stimulus presentation and data acquisition via the digitizing tablet; the time series of the x/y-coordinates of the pen position were sampled at 200 Hz. The spatial resolution of the digitizing tablet was 0.01 cm. The digitizing pen was attached to the anterior side of the right index finger such that the pen tip was approximately 1 cm proximal to the distal end of the finger.

A target localization task was employed, during which participants were instructed to use the available sensory information to localize target positions with their right index finger as accurately as possible. This target localization task was designed to mimic the multisensory-motor processes involved in hand localization, a critical factor for the accurate execution of goal-directed reaching movements [21;24]. No time constraints were imposed on the movements of the right hand. The goal of the task was to minimize the distance between the target and EP position of their right hand. Based on these constraints, the task involved minimal movement planning, but rather relied on the utilization of available sensory feedback to optimize localization performance. All targets were located in one of 4 positions to the left of the participants' midline (Figure 1B) and were presented in a pseudo-randomized order (e.g., each target was randomly presented once in a 4-target-sequence).

There were 3 experimental conditions, each referred to by the *target* modality during the localization task: visual (V), proprioceptive (P), and visual-proprioceptive (VP). During the *visual* condition, each participant positioned the pen inside a start circle (0.5 cm diameter) and one of four targets (0.5 cm diameter) appeared. The start circle turned green 750 ms after the target appeared, providing a 'GO' signal for movement onset. After the participant moved to the target position and remained stationary for 750 ms, the target disappeared and he/she returned to the start circle to begin the next trial. Importantly, no visual feedback was provided during the experimental conditions. In the visual condition, the index finger of the left hand remained in contact with a cloth dot (0.5 cm diameter) affixed to a wooden board inserted immediately below the lower tier of the apparatus (herein referred to as the left hand start position). The wooden board also served to indicate proprioceptive target locations for the subsequent experimental conditions.

During the *proprioceptive* (P) condition, each participant was instructed to move the digitizing pen attached to his/her right index finger to localize the position of the unseen left index finger below the digitizing tablet (Figure 1A). Prior to each trial, the participant actively moved the left hand from the start position along the wooden board away from his/her body until the left index finger was positioned at the target, demarcated by a felt cloth dot. The position of the left index finger underneath the tablet served as the proprioceptive target. The start circle turned green after 750 ms, at which time the participant moved the unseen right index finger on the tablet to the perceived location of the left index finger under the tablet. Once motionless for 750 ms, the participant placed the left hand in his/her lap and prepared for the next trial. During this time, an experimenter seated behind an opaque cloth inserted a new wooden board with a different target for the next trial. There were four exchangeable boards in total, each corresponding to one of the four proprioceptive target locations. The location of these four proprioceptive targets corresponded to the location of the visual targets presented on the monitor (Fig. 1B).

The *visual-proprioceptive* (VP) condition was nearly identical to the P condition. However, once the participant positioned his/her left index finger at the desired proprioceptive target location and their right index finger in the black start circle, a blue target circle appeared on the display monitor. This visual target circle indicated the position of the left index finger located on the underside of the tablet. Thus, during the VP condition, both visual and proprioceptive information were concurrently available to localize the target.

Practice sessions (10 trials per condition) were given for the three conditions to familiarize the participants with the task and to provide detailed verbal instructions. During the first eight practice trials, EP feedback was provided on the display monitor. No visual feedback of the digitizing pen was provided for the last two practice trials and the subsequent 16 baseline trials (4 per target) for each of the three conditions. The purpose of these baseline phases was to provide an assessment of localization performance for the different target modality conditions. Subsequently, participants completed an additional 32 VP trials. During 16 of these trials (randomly inserted), the position of the visual target did not match the position of the left index finger (i.e. incongruent stimuli). The incongruent trials were manipulated in the lateral direction only. For example, if the visual target stimulus was located at target position 1 (Figure 1B), the proprioceptive target stimulus was located at target position 2, and vice versa. The purpose of the incongruent trials was to place the visual and proprioceptive stimuli in conflict to determine the *relative* weights of the two sensory estimates. The experimental protocol (80 trials, not including practice) took approximately 45 minutes. Trials in which the participant lifted the pen from the tablet were excluded from analysis. Following completion of the protocol, participants completed a brief interview to assess participants' awareness of the incongruent phase. No participant reported any awareness of the perturbation.

Customized MATLAB™ (Mathworks, Natick, MA USA) scripts were used to apply a dual-pass 8th order Butterworth filter to the time series data (10 Hz cutoff frequency) and to mark movement onset and offset via an interactive algorithm implemented in previous research [7]. As localization accuracy was emphasized in the instructions to the participants, end-point position (EPP: x/y-coordinates) was the primary measure. Endpoint error (EPE), defined as the linear distance between EPP and the desired target position, was computed for each condition. It was hypothesized that localization performance, as assessed by EPE during the baseline conditions, would impact the relative weighting of the visual and proprioceptive estimates during the bimodal trials. Therefore, we computed a variable, X-Deviation (Figure 1C), to characterize the relative contributions of each modality to the multisensory estimate when vision and proprioception were in conflict. X-Deviation was computed by subtracting the EPP_x of the incongruent trials from the midpoint of the target locations (x-coordinate only). For example, an incongruent trial with the visual and proprioceptive target stimuli located at target positions 1 and 2, respectively, the EPP_x of the incongruent trial was subtracted from the midpoint between the first and second target positions (dashed line; Figure 1C). This midpoint represents the theoretical EPP_x assuming that the visual and proprioceptive target stimuli were *equally weighted*. An EPP_x shifted towards the visual target stimulus suggests that vision was more heavily weighted whereas an EPP_x shifted towards the proprioceptive target stimulus suggests that proprioception was more heavily weighted. The variable X-Deviation was transformed such that positive values indicated that the EPP of the incongruent trial was shifted to the visual estimate of target position and negative values indicated a shift to the proprioceptive estimate. The x-coordinate was of interest because the target stimuli in the incongruent trials were manipulated only in the x-direction.

Results

To examine the effects of age and baseline localization performance on multisensory-motor integration, we conducted a hierarchical multiple regression with X-Deviation as the dependent variable. The first block included only the participants' ages. The second block included the average EPE scores from each of the three baseline conditions (EPE_V , EPE_P , EPE_{VP}). A forward selection model ($p = 0.05$) was chosen for the second block so that the condition(s) that significantly accounted for variance in X-deviation would be kept in the final model. By inserting age as the first block, we could investigate the effects of baseline localization performance on multisensory-motor integration that were above and beyond the effects of age.

Age accounted for a significant amount of the variance in X-Deviation (Table 1; Model 1). Older children exhibited decreased X-Deviation values, suggesting that the proprioceptive estimate of target position contributed more to the multisensory estimate in comparison to young children (Fig. 2A). With respect to the role of baseline localization performance, the forward selection process eliminated EPE_V and EPE_{VP} from the final model. EPE_P accounted for a significant amount of variance in X-Deviation *above and beyond* that found for age (Table 1; $F\Delta = 6.62$; $p = 0.015$). Specifically, smaller EPE_P (i.e., better proprioceptive localization performance) was associated with a stronger contribution of the proprioceptive estimate of target position to the multisensory estimate (i.e., decreased X-Deviation) (Fig. 2A).

The main finding of this study is the relationship between proprioceptive localization and multisensory-motor integration after accounting for the effects of age (Fig. 2B). The residuals of the first regression block are depicted on the y-axis. Values equal to zero indicate that a model with only age as an independent variable predicted the exact value of X-Deviation. Residual values greater than zero indicate that the mean EPP of the incongruent trials was shifted *more* towards the visual estimate of target position than predicted by age alone. Similarly, the residuals of regressing EPE_P with age are shown on the x-axis. Positive values indicate that EPE_P was larger than that predicted by age. Critically, there is a positive relationship between the X-Dev and EPE_P residuals. This suggests that above and beyond the effects of age, better proprioceptive localization resulted in a shift towards the proprioceptive target position (i.e., decreased X-Deviation) when the unimodal estimates were in conflict. Thus, improvements in proprioceptive functioning resulted in an increased contribution of proprioception to the multisensory estimate of target position in 7- to 13-year-old children.

Discussion

These data indicate that 7- to 13-year-old children utilize information about unimodal estimation to flexibly re-weight redundant sensorimotor inputs. Previous research investigating multimodal localization suggested that 4- to 12-year-old children rely more heavily on vision when target position is provided by both visual and proprioceptive stimuli [26]. This conclusion was based on the similarity of the children's performance in the visual and visual-proprioceptive conditions. The current study placed the visual and proprioceptive estimates of target position in conflict, allowing us to determine the *relative contributions* of the two sensory modalities. Our data demonstrate that visual information is up-weighted only in the younger children, whereas proprioception appears to be up-weighted in the older children (Fig. 2). Moreover, above and beyond age-related changes, this up-weighting of proprioception increased as a function of improved proprioceptive localization, demonstrating that changes in multisensory-motor integration are driven by unimodal functioning. This suggests that the CNS in school-aged children are capable of acquiring and

storing distributions representing the accuracy of unimodal-motor functioning; and, these distributions are utilized in the integration of multisensory-motor information.

The current study demonstrates that multisensory-motor integration in 7- to 13-year old children cannot be explained by a 'dominant' sensory modality or by an integration mechanism that weights the two inputs equally. Rather, our results suggest that multisensory-motor integration in children is a flexible process influenced by the functioning of unimodal inputs. In the context of this study, improvements in proprioceptive localization in 7-13 year-old children resulted in an increased contribution of proprioception to the multisensory estimate; and, critically, this finding was independent of age. This result extends the findings of previous research examining multisensory-motor integration in postural control tasks [1;22]. In children younger than three years, vision has been considered the dominant modality and the contribution of other sensory inputs (i.e., proprioception) increased with age until approximately 7-10 years [22]. Older children exhibited adult-like multisensory integration, whereas the young children (i.e., 4- to 6-years) were thought to be in a transition period for multisensory integration.

Evidence from a variety of tasks suggests that the adult CNS utilizes *probabilistic* mechanisms to reduce the uncertainty inherent in multisensory-motor processing [e.g., 8;14;23;27]. In a probabilistic framework, available sensory information is differentially utilized, or flexibly 're-weighted', to reduce the uncertainty associated with a multisensory estimate. One such example includes the weighting of sensory inputs based on the inverse of the variability of the unimodal estimates [3;15;20;23]. Results from the current study suggest that multisensory-motor re-weighting is dependent on unimodal sensory functioning, a finding that is consistent with a probabilistic framework. However, localization distributions for each participant and each experimental condition are necessary to provide definitive evidence that children utilize probabilistic integration mechanisms for hand localization. This would require substantially more trials than employed in the current study. Nonetheless, these data and previous research [e.g., 23] suggest that the CNS of both school-aged children and adults can acquire and store distributions representing the accuracy of unimodal-motor functioning for hand localization. Moreover, these distributions influence the integration of multisensory-motor information, suggesting that the underlying *mechanisms* are similar across children and adults. This does not imply that these mechanisms are fully developed in school-aged children as both the mechanisms and the precision of unimodal-motor functioning are likely to be 'fine-tuned' during development. For example, previous developmental research indicated that *optimal* multimodal integration (i.e., computationally weighting inputs based on their precision) does not develop until approximately 10 years of age [10;17]. Collectively, our results and the research by Gori and colleagues [10] suggest that the accuracy and precision of unimodal estimates influence multisensory integration in children as young as 7 years of age; however, the redundant sensory inputs are not *optimally* integrated until approximately 10 years.

The current study demonstrated that improvements in *proprioceptive* functioning, in contrast to visual functioning, significantly influenced multisensory-motor integration. This is consistent with previous research demonstrating that static visual acuity is developed prior to the age range investigated in the current study [18] whereas proprioceptive acuity continues to improve throughout childhood and adolescence [9;19;25]. While not addressed in this study, future research should attempt to investigate the processes underlying the development of proprioceptive functioning.

Conclusion

Our results indicate that the relative contributions of vision and proprioception to a multisensory estimate are, at least partially, determined by the functioning of individual sensory modalities in 7- to 13-year-old children. Importantly, this finding is above and beyond the effects of age, suggesting that the age-related changes in multisensory integration reported in previous research [22] may be explained by improvements in unimodal functioning. Future research should probe the influence of these multisensory-motor processes on age-related improvements in sensorimotor performance [2;7;11;13;28].

Acknowledgments

This research was funded by NIH R01HD42527 (JEC) and R03HD050372 (FAK). We would like to thank the children and their parents for their participation; Marcio A. Oliveira for his insightful comments during manuscript preparation; and, Jeremy Rietschel for the construction of the experimental apparatus.

Reference List

1. Bair WN, Kiemel T, Jeka JJ, Clark JE. Development of multisensory reweighting for posture control in children. *Exp. Brain Res.* 2007; 183:435–446. [PubMed: 17665179]
2. Bo J, Contreras-Vidal JL, Kagerer FA, Clark JE. Effects of increased complexity of visuo-motor transformations on children's arm movements. *Hum Mov Sci.* 2006; 25:553–567. [PubMed: 17011657]
3. Bove J. Probabilistic method for integrating multiple sources of range data. *J Opt Soc Am.* 1990; 7:2193–2198.
4. Bullock D, Grossberg S. Neural dynamics of planned arm movements: emergent invariants and speed-accuracy properties during trajectory formation. *Psychol Rev.* 1988; 95:49–90. [PubMed: 3281179]
5. Buneo CA, Andersen RA. The posterior parietal cortex: sensorimotor interface for the planning and online control of visually guided movements. *Neuropsychologia.* 2006; 44:2594–2606. [PubMed: 16300804]
6. Contreras-Vidal JL. Development of forward models for hand localization and movement control in 6- to 10-year-old children. *Hum Mov Sci.* 2006; 25:634–645. [PubMed: 17011659]
7. Contreras-Vidal JL, Bo J, Boudreau JP, Clark JE. Development of visuomotor representations for hand movement in young children. *Exp Brain Res.* 2005; 162:155–164. [PubMed: 15586275]
8. Ernst MO, Banks MS. Humans integrate visual and haptic information in a statistically optimal fashion. *Nature.* 2002; 415:429–433. [PubMed: 11807554]
9. Goble DJ, Lewis CA, Hurvitz EA, Brown SH. Development of upper limb proprioceptive accuracy in children and adolescents. *Hum Mov Sci.* 2005; 24:155–170. [PubMed: 16043248]
10. Gori M, Del Viva M, Sandini G, Burr DC. Young children do not integrate visual and haptic form information. *Curr Biol.* 2008; 18:694–698. [PubMed: 18450446]
11. Hay L. Spatial-temporal analysis of movements in children: motor programs versus feedback in the development of reaching. *J. Mot. Behav.* 1979; 11:189–200.
12. Henderson, SE.; Sugden, DA. Movement Assessment Battery for Children. The Psychological Corporation; London, UK: 1992.
13. King BR, Kagerer FA, Contreras-Vidal JL, Clark JE. Evidence for multisensory spatial-to-motor transformations in aiming movements of children. *J Neurophysiol.* 2009; 101:315–322. [PubMed: 18987123]
14. Kording KP, Wolpert DM. Bayesian integration in sensorimotor learning. *Nature.* 2004; 427:244–247. [PubMed: 14724638]
15. Landy MS, Maloney LT, Johnston EB, Young M. Measurement and modeling of depth cue combination: in defense of weak fusion. *Vision Res.* 1995; 35:389–412. [PubMed: 7892735]

16. Mon-Williams MA, Wann JP, Pascal E. Visual-proprioceptive mapping in children with developmental coordination disorder. *Dev Med Child Neurol.* 1999; 41:247–254. [PubMed: 10355808]
17. Nardini M, Jones P, Bedford R, Braddick O. Development of cue integration in human navigation. *Curr Biol.* 2008; 18:689–693. [PubMed: 18450447]
18. Nelson LB, Rubin SE, Wagner RS, Breton ME. Developmental aspects in the assessment of visual function in young children. *Pediatrics.* 1984; 73:375. [PubMed: 6701062]
19. Pickett K, Konczak J. Measuring kinaesthetic sensitivity in typically developing children. *Dev Med Child Neurol.* 2009; 51:711–716. [PubMed: 19207300]
20. Searle CL, Braida LD, Davis MF, Colburn HS. Model for auditory localization. *J Acoust Soc Am.* 1976; 60:1164–1175. [PubMed: 977843]
21. Shadmehr, R.; Wise, SP. *The Computational Neurobiology of Reaching and Pointing.* The MIT Press; Cambridge, Massachusetts: 2005.
22. Shumway-Cook A, Woollacott MH. The growth of stability: postural control from a development perspective. *J. Mot. Behav.* 1985; 17:131–147. [PubMed: 15140688]
23. van Beers RJ, Sittig AC, van der Gon JJD. Integration of proprioceptive and visual position-information: An experimentally supported model. *J Neurophysiol.* 1999; 81:1355–1364. [PubMed: 10085361]
24. Vindras P, Desmurget M, Prablanc C, Viviani P. Pointing errors reflect biases in the perception of the initial hand position. *J Neurophysiol.* 1998; 79:3290–3294. [PubMed: 9636129]
25. Visser J, Geuze RH. Kinaesthetic acuity in adolescent boys: a longitudinal study. *Dev Med Child Neurol.* 2000; 42:93–96. [PubMed: 10698325]
26. von Hofsten C, Rosblad B. The integration of sensory information in the development of precise manual pointing. *Neuropsychologia.* 1988; 26:805–821. [PubMed: 3194047]
27. Wolpert DM. Probabilistic models in human sensorimotor control. *Hum Mov Sci.* 2007; 26:511–524. [PubMed: 17628731]
28. Yan JH, Thomas KT, Stelmach GE, Thomas JR. Developmental differences in children's ballistic aiming movements of the arm. *Percept Mot Skills.* 2003; 96:589–598. [PubMed: 12776841]

Figure 1.

Experimental set-up and protocol. **A.** Visual stimuli were presented via a computer monitor on the top tier of the apparatus whereas proprioceptive stimuli were provided by the position of the unseen left index finger below the digitizing tablet. Participants moved their occluded right hand on top of the tablet to localize visual, proprioceptive, or simultaneous visual-proprioceptive target stimuli as accurately as possible. **B.** The four target locations (black circles) are shown with respect to the right hand's start position (gray circle). **C.** Computation of the variable X-Dev. The x-coordinate end-point position (EPP_x) of an incongruent trial was subtracted from the x-coordinate midpoint of the two target positions for that incongruent trial (vertical dashed line). Values were transformed so that a positive X-Dev value indicated the EPP was closer to the visual (V) target whereas a negative value indicated the EPP was closer to the proprioceptive (P) target.

Figure 2.

A. Scatter plot depicting X-Dev as a function of EPE_p and age. Plane and corresponding color bar depict predicted X-Dev values. **B.** Partial regression plot depicting X-Dev as a function of EPE_p, controlling for the effects of age.

Table 1

Hierarchical Regression

Model	Parameters	β	S.E.	R ²	R ² Change	F Change	df	Sig. F Change
1 ^a	Constant	3.21	1.33					
	Age	-0.35	0.13	0.161	0.161	6.72	1,35	0.014
2 ^b	Constant	1.36	1.43					
	Age	-0.30	0.13	0.298	0.137	6.62	1,34	0.015
	EPE _p	0.54	0.21					

^aModel 1 represents the first block which included only age as a predictor.

^bModel 2 includes the first and second blocks. EPE_y and EPE_{VP} were excluded through forward selection ($p > 0.05$).