Full length article

Multisensory factors in postural control: Varieties of visual and haptic effects

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A B S T R A C T

Background Previous work on balance control in children and adults highlights the importance of multisensory information. Work in this vein has examined two principal input sources – the role of visual and haptic information on balance. Recent work has explored the impact of a different form of haptic input – object holding – on balance in young infants.

Research question This experiment examined the impact of simultaneous visual input and haptic input on balance in children and adults, employing two novel forms of haptic input.

Methods Static balance was measured in 3–5 year olds, 7–9 year olds, and young adults, in the presence of all possible combinations of manipulated visual input (eyes open, eyes closed) and haptic input (no touch, object hold, touch an unstable support, touch a stable support).

Results Analysis of postural stability (mean velocity) indicated that stability was influenced by visual input, haptic input, and age group. For visual input stability increased in eyes open versus eyes closed conditions. For haptic input, stability systematically increased with increasing levels of fixed haptic input (e.g., no touch, object hold, unstable touch, stable touch). Stability also increased as a function of increasing age group. There were no interactions between the factors.

Significance The finding that the two novel forms of haptic input – object hold and touch with an unstable support surface – increased stability relative to no touch input, but not as much as touch with a stable support, indicates that children use haptic information in a self-referential fashion for controlling posture. The failure to observe any interactions between visual and haptic inputs with age suggests that multisensory processing is generally additive across development, and has implications for the occurrence of sensory weighting across developmental epochs.

1. Multisensory factors in postural control: Varieties of visual and haptic effects

For many years posture has been intrinsically recognized as multisensory [1], with such influences applicable across the lifespan, from infancy through to adulthood [2]. Of the inputs influencing balance, the two most highly studied factors are vision and haptics. Evidence for visual influences is considerable. Such evidence includes well-known examples such as Lee's moving room [3], and the similarly well-known, albeit not as visually dramatic, Romberg effect [4]. Both sets of results have been convincingly demonstrated with children [5–7] and adults [8]. Similarly, studies of children [9,10] and adults [11,12] examining haptic influences on balance suggests that lightly touching a support surface stabilizes balance, relative to not touching a surface, and that an oscillating touch surface can drive sway.

Subsequent work has extended these findings by varying the content of such inputs. For example, a common visual manipulation has been to present oscillatory flow varying in frequency or amplitude [6,13,14]. For haptic input, one line of work has explored the frictional properties of the support surface [15,16]. One intriguing extension to work on haptic influences has been provided by Claxton, Haddad and colleagues [17,18]. These authors demonstrated that the simple act of holding a toy influences balance, with 11-month-old infants showing more complex body sway [18] and increased stability for longer periods of time [17] when holding a toy, compared to not holding a toy. These authors suggested that the increased stability arises through engagement in a goal-directed task, one that ultimately requires attention; this result converges with other data on children's stability in goal-directed tasks [19].

These findings suggest that haptic input can lead to increased stability irrespective of its link to a stable support surface. On a real-world basis, such results raise issues related to the role of multisensory

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information in participants with a range of developmental disorders (e.g., developmental coordination disorder, cerebral palsy, autism). This finding also highlights a variety of gaps in our knowledge of the impact of haptic input on balance, gaps that the current study addresses. First, it is of interest to determine whether this result is applicable across ages. In this regard, it is possible that the observed increased stability resulted from the fact that newly standing infants are generally highly unstable. Given that baseline stability at this age is substantially lower, it might simply be easier to increase stability for such a group. Convergent with this possibility, Chen, Lee and Aruin [20] found that object holding failed to impact anticipatory or compensatory postural responses in adults. Thus, the first goal of this project was to explore the impact of object holding across a wider age range of participants, specifically children between 3 and 9 years, and adults. This age range is of interest given literature suggesting that the adoption of adult-like postural control occurs over this time [5,6,21].

The second goal of this project was to further explore the actual impact of object holding on posture. Although Claxton et al. [17,18] demonstrated increased stability during object holding, it is not clear whether this stability was comparable to that found in studies investigating the impact of light fingertip contact on posture. To make such a comparison requires examining stability during object holding and light fingertip contact.

A third goal of this project was to explore the impact of other forms of haptic input on posture. Given the previous goal-directed argument, any form of haptic input that is goal-directed should have a similar effect on posture. This study tested this idea by employing a haptic input that was similar to previous studies on light fingertip contact, but that was unconnected to a stable support.

A fourth goal of this project was to look at how these visual and haptic inputs interact within a developmental context. One question that has arisen in multisensory investigations of posture is whether visual and haptic inputs contribute additively versus interactively to balance. In work with adults, Jeka and Lackner [12] observed an interaction between visual and haptic inputs. Intriguingly, although Jeka, Oie and Kiemel [22] found an additive model inadequate to explain postural sway driven by simultaneous visual and tactile inputs, these authors nevertheless argued for a linear process given that the observed postural control was close to the equilibrium point for upright stability. Accordingly, the additive versus interactive nature of multisensory balance control remains unclear, particularly within a developmental context.

2. Methods

2.1. Participants

This report is based on a final sample of 54 participants with usable data, including 18 3- to 5-year-olds, (*M* age of 4.44 yrs, *SD* = 0.93), 18 7- to 9-year-olds (*M* age of 7.83, *SD* = 0.99), and 16 young adults (*M* age = 20.65 yrs, *SD* = 1.92); these sample sizes are typical of postural control research with both children and adults. An additional 16 participants (nine 3–5 year olds, four 7–9 year olds, three adults) participated but their data were not usable. For the children, the principal reason for exclusion was a generally uncooperative attitude, combined with an inability to stand still. The adults were excluded because of errors in data collection. Children were recruited from an existing database at the University of Toronto Scarborough, and received a toy for participating. Adults were recruited through an introductory psychology course, or by word of mouth, and received course credit or volunteered their time. The experimental procedures and protocol were approved by the University of Toronto's Research Ethics Board.

2.2. Materials

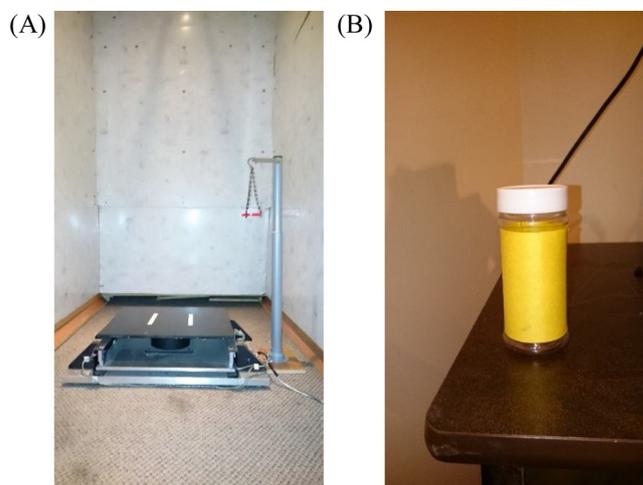A custom built force platform [see 6,13]. collected all postural sway

Fig. 1. The experimental apparatus employed in this experiment, including (A) the force platform and touch surface apparatus, and (B) the cylinder held by participants. For the stable surface participants touched the plastic circular surface on the top of the stand. For the unstable touch surface participants touched the hanging plastic circular surface. Note that the height of the stand was adjustable so as to allow touch in both conditions at the same height.

measures. The force platform was sampled at 50 Hz. Anterior-posterior (AP) and medio-lateral (ML) sway vectors were used to calculate resultant distance (RD) sway vectors.

A hollow plastic cylinder (4 g), 12.9 cm in length and 5.5 cm in diameter, was the held object. An adjustable stand positioned to the right of the platform provided a flat circular (3.7 cm diameter) support surface for participants to touch. Attached to this stand was a metal arm with a hanging support surface (7.5 cm diameter). Both support surfaces were adjusted to fingertip level for participants on a trial by trial basis. Fig. 1 presents photographs showing the force platform, the adjustable touch surface apparatus, and the plastic cylinder that was held by participants.

2.3. Experimental design

This study contained two within-subjects, and one between-subjects, variables. The first within-subjects variable manipulated the presence versus absence of visual input, with eyes open and eyes closed conditions. The second within-subjects variable manipulated haptic input. This variable contained four levels, including no touch, object hold, unstable touch (light fingertip contact with an unstable support surface) and stable touch (light fingertip contact with a stable support surface) conditions. These two factors were crossed, producing eight trials in total, with participants receiving two randomly ordered blocks of these eight trials. The between-subjects manipulation involved the three age groups.

2.4. Procedure

For the children, parents provided informed consent, and the visual and haptic conditions were explained. For visual manipulations, children were asked to stand still, with their eyes open or closed. For haptic manipulations, children were asked to stand with their arms at their sides (no touch), to hold an object in their right hand (object hold), to lightly touch the hanging surface with their right index finger (unstable touch), and to lightly touch the surface at the top of the stand with their right index finger (stable touch). Children stood with their feet shoulder width apart, facing away from the experimenter, although the experimenter could monitor children's faces to ensure they kept their eyes closed during dark conditions. Children were instructed to remain still and quiet by playing the "statue game" in which they competed with an

experimenter to see who was a better statue. For adults, the procedure was similar, although because adults would stand still on their own the statue game was unnecessary.

All trials were 30 s, with enough time between trials to give instructions for the next trial and to adjust the stand when necessary. If participants moved or spoke during the trial, the trial was rerun. The entire experiment took about 45–60 min for children, and 30 min for adults.

2.5. Data preprocessing

Because RD vectors best characterize participants' postural sway, all analyses employed this measure.[1] RD vectors were filtered with a 4th order Butterworth low-pass filter with a 5 Hz cutoff, and then used to calculate stability measures used in previous work [23–25] using custom Matlab scripts. Measures included time-domain distance parameters (e.g., mean and root mean square [RMS] distance, mean and RMS velocity), time-domain area measures (e.g., 95% confidence circle and ellipse areas), and time-domain hybrid measures (e.g., sway area). Although these measures do show differences for characterizing stability [e.g., see 24, 25], they also converge in stability descriptions across conditions. Based on previous work the most useful measure of stability is velocity of sway (mean or RMS velocity). Raymakers et al. [25], for instance, found that velocity showed the most consistent differences between experimental manipulations, age, and health status. Accordingly, these analyses focused on the mean velocity of postural displacement.[2]

3. Results

Velocity values were averaged across the two repetitions[3] and were analyzed in a three-way ANOVA with the within-subjects variables of *Visual Input* (eyes open, eyes closed) and *Haptic Input* (no touch, object hold, unstable touch, stable touch), and the between-subjects variable of *Age Group* (3–5 years, 7–9 years, adults). This analysis produced main effects for *Visual Input*, $F(1, 49) = 50.21$, $MSE = 0.25$, $p < .001$, $np^2 = 0.51$, *Haptic Input*, $F(3, 147) = 7.53$, $MSE = 0.13$, $p < .001$, $np^2 = 0.13$, and *Age Group*, $F(2, 49) = 40.68$, $MSE = 2.93$, $p < .001$, $np^2 = 0.62$. None of the two-way interactions were significant, nor was the three-way interaction. Fig. 2 graphs these main effects, and for informational purposes, the three-way interaction.

Follow-up comparisons, employing Bonferroni corrections, were conducted on the main effects of *Haptic Input* and *Age Group*; because *Visual Input* contained only two levels the ANOVA result indicates greater stability with eyes open than eyes closed. Fig. 2 indicates the results of these comparisons. For *Age Group* there were significant differences between all ages, with the youngest participants demonstrating the least stability and the oldest participants showing the most stability. Of more interest were the comparisons across the *Haptic Input* conditions. Posture was increasingly more stable as the type of haptic input was more fixed. As shown in Fig. 2, postural sway was the least stable in the no touch condition, the most stable in the stable touch condition, and intermediate in the object hold and unstable touch conditions. Although not fully consistent, the pattern of condition differences supports this description.

To further substantiate this pattern, a subsidiary 3-way ANOVA was conducted using a modified *Haptic Input* variable – no touch, averaged

object hold/unstable touch, and stable touch. The critical result from this analysis was the main effect for *Haptic Input*, $F(2, 98) = 12.22$, $MSE = 0.12$, $p < .001$, $np^2 = 0.20$, and *Age Group*, $F(2, 49) = 39.80$, $MSE = 2.28$, $p < .001$, $np^2 = 0.62$. Subsequent Bonferroni comparisons revealed significant differences between all pairs of means. Accordingly, the object hold and unstable touch conditions resulted in increased stability relative to no haptic input, but decreased stability relative to stable haptic input.

4. Discussion

These findings provide concise responses to the original four goals of this study. With regards to the first goal, this study clearly demonstrates that the impact of holding an object on posture is applicable across a wider range of ages than previously tested [17,18]. Notably, the fact that this finding extends to more motorically skilled children and adults suggests that the effect of holding an object on postural sway is not simply due to motor immaturity which has been previously observed in 11-month-olds [17,18]. Moreover, the effect of holding an object on increasing postural stability was independent of individuals' baseline motor skill. Second, this study demonstrated that the impact of object holding on balance is not equivalent to that observed through simple light fingertip contact. Our findings suggest that although object holding reduces instability relative to no touch information, object holding offers does not provide equivalent postural stability as would occur with light fingertip contact with a stable support surface. Third, this study confirms that there is, indeed, a general impact of haptic input on balance. In this case, light fingertip contact with an unstable support surface also influenced stability in a highly comparable manner as that of object holding. Light fingertip contact with an unstable surface increased stability relative to no touch, but did not offer as much stability compared to contact with a stable support. And finally, this study found no evidence of interaction between visual and haptic inputs within a developmental context; this last point will be further addressed subsequently.

In a very general fashion these findings replicate and extend previous on multisensory postural control. Unsurprisingly, these findings replicate the well-known results that postural stability increases in lit (e.g., eyes open) relative to dark (e.g., eyes closed) environments, and that light fingertip contact with a stable support increases stability relative to no fingertip contact. Of greater novelty is the finding that postural stability increased for touch not tied to a stable support. Specifically, stability changed when participants held an object in their hands, or received fingertip contact from an unstable support surface; this last finding has not, to our knowledge, been documented in the field.

Together these results have a variety of implications. Most fundamentally, these results argue against the locus of this effect arising from a mechanism that focuses participants' attention on aspects *other* than maintaining stability [17,18]. Although such a hypothesis can explain increased stability in object hold conditions relative to no touch conditions, it does not explain the decreased stability relative to the stable touch condition, given that these latter three contexts involving touching objects or surfaces do not intuitively seem to vary appreciably in their goal-directed natures.

Of course, the preceding discussion begs the question of why such haptic inputs influence postural stability in the first place, given that the benefit of light fingertip contact far exceeds any possible advantage as a result of passive reactive forces arising through such contact [e.g., [26]]. One possible explanation is that light fingertip contact provides haptic stimulation that make participants more aware of body sway, thus enabling them to counteract this sway [27]. As described by Lackner and DiZio [28], "…contact with a stable support serves as a sensory-motor probe for controlling body position. Stabilizing the finger probe at the contact surface, by minimizing force changes at the fingertip, automatically stabilizes the body" (p. 283). Thus, contact
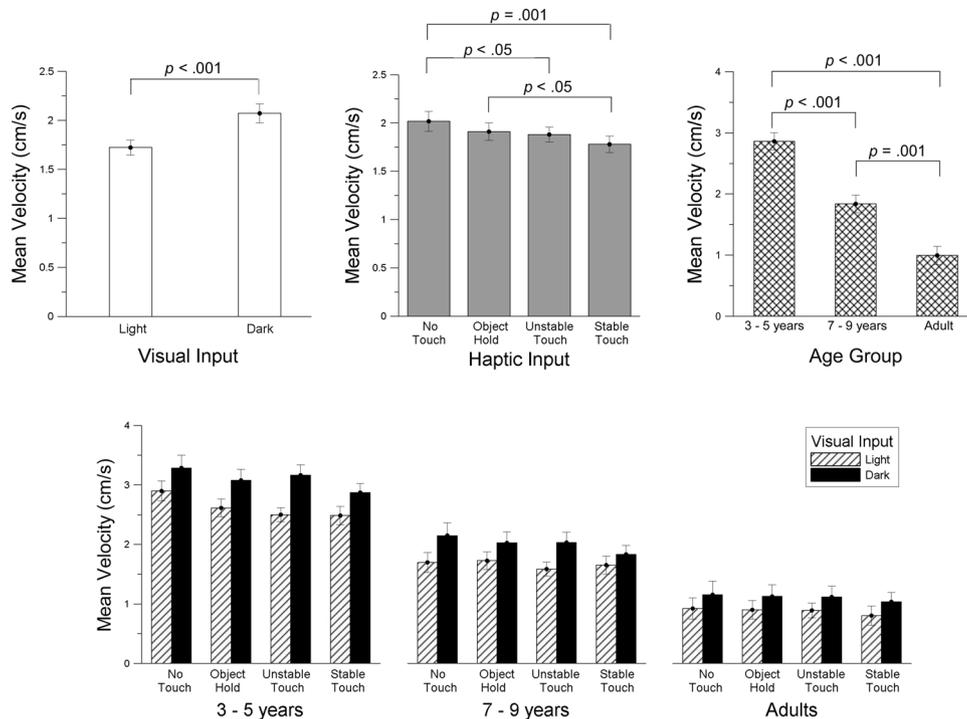
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[1] Subsidiary analyses also employed AP sway recordings, and produced comparable findings to the RD sway analyses reported in this manuscript

[2] Analyses of other parameters produced comparable, albeit not identical, effects.

[3] For two participants (one 3 – 5 year old and one 7 – 9 year old) data from one trial in one of the blocks was missing; accordingly data for these conditions for each participant was only based on a single repetition.

Fig. 2. Mean velocity (cm/s) and standard error as a function of the main effects for *Visual Input*, *Haptic Input*, and *Age Group*, along with the three-way interaction between these factors.

information provides observers with referential information regarding their own sway, enabling better compensatory postural adjustments.

Although reasonable with respect to these findings, certain questions do remain. The fact that the unstable touch condition increased stability relative to the no touch condition, but less than the stable touch condition, is perfectly consistent with this idea. Because unstable touch is ultimately ambiguous in indicating body sway, it is a less reliable referent than stable touch. Applied to object touch, however, this argument is less compelling in that the haptic input provides, at best, only indirect information about body sway through, say, an increased awareness of arm swing. Albeit possible, this explanation seems significantly more speculative, although it could be tested by comparing sway during object holding with the arm externally stabilized versus unstabilized.

Another intriguing finding of this study was its lack of interaction between the factors. Accordingly, these findings argue strongly for additive effects of visual and haptic input, a finding that converges with Jeka et al.'s [22] conclusions. More generally, a discussion of additive versus interactive effects highlights the issue of the weighting of sensory inputs in postural control, a question that has been addressed in work on sensory reweighting [14]. Developmentally, such work has demonstrated that whereas adults and older children (6 and 8 years) are adept at reweighting sensory inputs when demanded by the experimental context, younger children (4 years) display significantly less adaptability. Although not explicitly quantifying the weights of sensory inputs, such work does suggest that the weighting of sensory inputs could vary across age and experimental contexts.

Recently, Schmuckler [29] began addressing this question by predicting stability from codings of the presence versus absence, and relative stability, of multisensory inputs. This work aggregated data drawn from multiple experimental contexts, including manipulating presence versus absence of visual and haptic input, oscillatory optic flow at varying frequencies, and proprioceptive input provided by differing bases of support, and ages, including 3–11 year olds and adults. These analyses indicated a shift in the relative weighting of sensory inputs across developmental time, and the introduction of an

interactive factor, in predicting stability. Although preliminary, this work demonstrates the viability of such a cross-experiment approach in addressing the question of the weighting of sensory factors.

Interestingly, other than an overall effect of age, the differences seen for changing visual and haptic input remained constant across age groups. This lack of any age interaction is surprising given that the current age groupings were chosen so as to bracket the acquisition of a mature level of postural functioning [5,21]. Moreover, previous work does suggest changes in multisensory postural control throughout the lifespan, from childhood [9,30] through to old age [14]. Given this literature, that there were no consistent developmental differences in multisensory influences on balance is surprising (and truthfully, disheartening). Although one might be concerned that the sample size in this study was not sufficient to detect such differences, the previous literature [9,14,30] suggests that this sample size should be sufficient. For instance, testing 30 children (10 each at 4, 6, and 8 years), Barela et al. [9] found developmental differences in the use of haptic input for balance. Similarly, testing 41 children between 4 and 10 years, Bair et al. [30] observed developmental differences in inter-modal reweighting of sensory inputs.

Accordingly, when interpreting this result one should consider that the ANOVA design that assessed the impact of visual and haptic inputs might not be sensitive enough to variation in the use of multisensory information across development. Using a large scale focus, Schmuckler (2018) did suggest that the weighting of sensory factors might vary across developmental groups. Although admittedly only suggestive at the moment, such findings do provide a tantalizing hint that looking across experimental contexts could reveal more subtle developmental differences in the use of multisensory input.

In conclusion, the goal of the current project was to explore the use of multisensory input, across participants ranging from young children to young adults. This work demonstrated that both visual and haptic inputs contributed to balance, with novel forms of haptic input contributing relative to their value as a source of referential balance information. More generally, this work again highlights the central role played by multisensory factors in postural control, with such

multisensory information central to balance even at young ages.

Conflict of interest statement

Neither of the authors have any financial or personal relationships with other people or organisations that could have inappropriately influenced their work.

Author note

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