Appendix 1
Exclusion Criteria and Screening Tests

Exclusion criteria were: visual conditions affecting daily function; vestibular conditions; lower extremity numbness or somatosensory loss; neurological disorders; cognitive decline; recent musculoskeletal changes; insufficient endurance; and taking more than six prescription medications.[23]
All volunteers not previously excluded underwent clinical screening by an experienced licensed physical therapist (PT). Screening tests included cognition (Mini-Mental Status Exam), visual acuity (Snellen Chart), vestibular loss (Head Thrust and Dynamic Visual Acuity), and lower extremity somatosensory loss (proprioception, vibration with tuning fork, and touch/pressure with Semmes-Winstein Monofilament screening set) see below.

Volunteers with clinically detectable cognitive or peripheral sensory loss were excluded. The exclusion of volunteers with significant peripheral sensory loss was critical since this loss renders a sense 'unavailable' and thus not subject to experimental manipulation. Most importantly, because MSR is a central integration process, we could not expect the central nervous system to respond to changes in sensory stimuli not detectable in the periphery.

Clinical Screening Tests Used for Inclusion/Exclusion Criteria

Mental status. Mental status was measured using the Mini-Mental Status Exam; volunteers with scores of less than 24 were excluded so that informed consent protections were met.[60]

Visual acuity. Visual acuity was tested using a standard Snellen chart; volunteers were permitted to wear corrective lenses for this test. Older adults with 20/50 vision or better were accepted.

Somatosensation. Bilateral lower extremity somatosensation was tested using standard clinical tests of proprioception and vibration (128 Hz tuning fork) at the first metatarsal head and malleolus, and touch was tested with a Semmes-Winstein monofilament screening test on the sole of the foot.[61,62] Volunteers were excluded if, on either leg, (1) any of the three senses was absent, (2) touch was impaired, (3) ankle proprioception *or* vibration was impaired, or (4) metatarsal vibration *and* proprioception were both impaired. Subjects with either present vibration *or* present proprioception at the first metatarsal were included. We use the term 'sufficiently intact' somatosensation because we recognize that these clinical screening tests lack optimal sensitivity, but they do confirm that somatsensory stimuli are received by the brain and consciously perceived there. This is important because the ability of the brain to respond to somatosensory information was being investigated in the MSR test.

Vestibular loss. Complete bilateral peripheral vestibular loss leads to gaze instability not necessarily dizziness, and thus might have been missed by the Eligibility Questionnaire. The Head Thrust maneuver and Dynamic Visual Acuity test were used to rule out complete bilateral peripheral vestibular loss.[63] The Head Thrust maneuver was performed in both the sagittal and frontal planes, older adults with abnormal "catch up" saccades were excluded. The Dynamic Visual Acuity Test was performed using a standard Snellen chart and rapid, small passive head oscillations (about 2 Hz), volunteers who were unable to read within three lines of the smallest line read correctly with the head still were excluded. Responses from the questionnaire indicated that subjects did not have any known vestibular conditions and did not experience dizziness or vertigo, so dizziness-related tests were not performed. While these screening methods are imprecise and do not ensure completely intact peripheral vestibular function, they were useful to rule out complete bilateral and uncompensated unilateral loss. We thus assumed a sufficient level of peripheral vestibular function was present for this MSR experiment, which did not manipulate vestibular inputs (e.g., galvanic stimulation) or challenge the vestibular system (e.g., head motion) in any way during MSR testing. The laboratory MSR test measured postural responses in five conditions with systematically altered visual and touch motion stimuli. We assumed that any undetected declines in vestibular function would not substantially alter the pattern of MSR results as all conditions would be equally influenced by any peripheral vestibular deficit.

Appendix 2
Clinical Outcome Measures

Activities-specific Balance Confidence Scale. The ABC Scale is a self-reported measure of balance confidence that reflects the self-perceived balance abilities of the older adult.[40] On a scale from 0% (not at all confident) to 100% (completely confident), subjects indicate, for each item describing a real-life balance challenge, how confident they are that they could perform the activity without a loss of balance. Scores from each item were summed and then divided by the total number of items to obtain an average overall balance confidence score. The ABC Scale was included to permit comparison of objectively measured changes in balance performance following training to subjective perceptions of balance abilities.

Berg Balance Scale. The Berg Balance Scale is a 14 item test battery with a 5 point ordinal rating scale (0-4).[37] Task difficulty increases from easy (sit-to-stand) to difficult (stand on one leg). Scores from each of the items are summed. This test was included as it is widely used clinically for fall risk assessment, and scores correlate highly with functional abilities and fall-risk.[39,54,64,65] This test served as our global balance performance and fall-risk measure.

Limits of Stability®[ll]. The Limits of Stability [LOS] test is a quantitative test of dynamic balance that reflects volitional center-of-gravity control. The LOS protocol has been described previously elsewhere.[30,48,50] Briefly, subjects stand on a stable forceplate that measures postural sway. They view a computer monitor that displays a cursor representing the position of their center-of-gravity which moves when the individual weight-shifts. Participants are asked to shift their weight (move the cursor) from a midline position outward as far as possible to eight consecutive targets placed at a perimeter whose distance is determined by individual height.

For this study, the LOS test was administered twice at each of the three testing sessions, with a seated rest in between tests. The first LOS test was considered a familiarization session; the sum of the eight Maximum Excursion scores from the second test was used for analysis.

The LOS test was included because one of the measures provided by this test is maximum center-of-gravity excursion, which is strongly associated with fall risk.[50] The sensory-challenge exercise intervention intentionally avoided dynamic balance training. However, we hypothesized that improvements in MSR might lead to improved perception of position and motion in space, which might then be followed by improved center-of-gravity control and modest increases in center-of-gravity excursion.

Range of Motion and Strength. Limited lower extremity range of motion and especially reduced lower extremity strength are musculo-skeletal impairments associated with imbalance and fall-risk.[41,42] Improvements in range-of-motion and strength may thus improve balance and reduce fall risk. However, a main purpose of this study was to investigate whether MSR might be one mechanism through which sensory-challenge exercise produces its known positive effects on balance performance. It was important, then, to measure range-of-motion and strength so that if improvement in balance performance occurred it could be attributed to improved MSR, not increased range-of-motion or strength. Range of motion and strength were assessed bilaterally for the following joint motions: hip flexion, extension, abduction, adduction; knee flexion and extension; and ankle dorsiflexion and plantarflexion.

Range of motion was measured with a manual goniometer. For each joint, the actual range (in degrees) was subtracted from the normal range to obtain a ‘degree of limitation’ score. A summary range-of-motion limitation score was obtained by adding the number of degrees of limitation found at each joint.

[ll] NeuroCom Internattional Inc., Clackamas, OR; now Natus Medical, Inc., Pleasanton, CA

Strength was measured with a handheld dynamometer.[*] For each motion, three trials were performed. The peak number of pounds of force was recorded. A summary strength score was obtained by adding the peak force produced at each of the 16 measured joint motions.

Composite range-of-motion and strength scores were used as this study was not concerned with precise changes at individual joints, and to limit the number of variables being considered. Both goniometry and dynamometry produce interval scores that may legitimately be summed to produce an overall score that reflects impairments of range-of-motion and strength in the lower extremities.[43,44] Because the sensory-challenge exercise program was designed to facilitate MSR, and included no stretching or resistance exercises, we did not expect any post-training changes in range-of-motion or strength.

Sensory Organization Test®[†]. The *Sensory Organization Test®* [SOT] is the most quantitative clinical test of central sensory integration impairments. The SOT protocol has been described extensively elsewhere.[3,14,16,18] Briefly, participants stand within a movable visual surround booth on a movable forceplate that measures postural sway under six sensory conditions. Eyes open and eyes closed conditions are used to make vision available or unavailable, respectively. Both the surface and the visual surround can be individually sway-referenced to render somatosensory or visual inputs inaccurate, or jointly sway-referenced to render both somatosensory and visual inputs inaccurate. Combinations of these sensory manipulations are used to identify normal or abnormal use of somatosensory, vision, and vestibular inputs for postural control. Three consecutive 20 second trials in each condition are provided. Many older adults demonstrate instability on the first trials of conditions 5 and 6, when both vision and somatosensory inputs are altered and greater reliance on vestibular inputs is required. Healthy older adults typically demonstrate improvement on subsequent trials, while fall-prone elders do not.[13]

For this study, the SOT was administered twice at each of the three testing sessions, with a seated rest in between tests. The first SOT test was considered a familiarization session; SOT Composite scores from the second test were used for analysis.[66] The SOT Composite score is a weighted average of the scores from the six sensory conditions.

The SOT was included because it is the standardized clinical test that measures MSR in the time domain, versus our laboratory tests of MSR in the frequency domain. Further, the SOT has been frequently used in previous studies of MSR and sensory training.[29,30] It was important to know if the participants in this study performed similarly on the pre-training SOT tests as did participants in these prior studies of sensory integration so that we could compare our results to the existing literature. We expected that changes in SOT scores would occur concomitantly with changes in the laboratory MSR results as both forms of testing measure MSR, and that is what the sensory-challenge exercise program was designed to improve.

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[*] Chatillon CSD100, AMETEK, Inc., Largo, FL

[†] NeuroCom International Inc., Clackamas, OR; now Natus Medical, Inc., Pleasanton, CA

Appendix 3
Sensory Challenge Balance Exercise Program

Sensory-challenge balance exercises challenge balance through the intentional manipulation of the environment to render one or more sensory inputs unavailable, inaccurate, or variable (unpredictable). For example, balance practice with eyes closed renders vision unavailable, practice while standing on compliant foam renders somatosensation inaccurate, and practice with head shaking makes vestibular inputs variable. These changes in environmental conditions require MSR for successful balance control. Dynamic balance exercises like Tai Chi, functional balance activities like sit-to-stand training, and reactive balance exercises using perturbations are all valuable, but are not considered sensory-challenge balance exercises because no intentional manipulation of visual, vestibular or somatosensory inputs occurs.

Rationale

The goal of the exercise program was to improve (1) estimation of body position and motion in space and (2) adaptation to changing sensory environments. Development of the exercise protocol was based on concepts familiar to clinicians who use the Sensory Organization Test® or Clinical Test for Sensory Interaction on Balance (CTSIB). Through alteration of the environment in which postural control must be maintained (visual conditions, surface conditions, or both) clinicians can render a sensory input unavailable (e.g., eyes closed renders vision unavailable) or inaccurate (e.g., standing on compliant foam renders somatosenation inaccurate). This forces the central nervous system [CNS] to reduce reliance on [down-weight] unavailable or inaccurate sensory inputs, and increase reliance on [up-weight] the available and accurate ones, in order to accurately estimate body position and motion in space. Repeated practice of balance exercises in conditions requiring multi-sensory reweighting should improve these estimation and adaptation abilities, which in turn should contribute to improved balance.

Materials

All exercises were performed on a SMART Balance Master® (formerly NeuroCom International, Inc., Clackamas, OR; now Natus Medical, Inc., Pleasanton, CA), a computerized balance testing and training device. This equipment provides operator-controlled surface and/or visual environment motion that can be finely graded up or down in small, quantifiable increments that are precisely repeatable between sessions and participants, and closely matched to participant ability levels. If desired, the equipment also provides visual feedback about center-of-gravity position and motion to promote early motor learning.

All PT/PTA trainers responsible for the delivery of the exercise program were trained in the use of the equipment, and the progression protocol, by one author who is a PT with multiple years of experience using the equipment and training other clinicians to use it. Trainers used tracking forms (one per participant) to record the practice conditions and advancement of exercise difficulty levels within and across the 16 exercise sessions.

Procedures

The specific sensory-challenge balance exercise protocol used in this study systematically applied the general concepts described above. Within each exercise session participants practiced balance control under varied sensory conditions, to improve their ability to up- or down-weight somatosensory, visual and vestibular inputs. Across the 16 exercise sessions the balance control task and environmental conditions became progressively more demanding to achieve the most improvement possible.

The frequency and duration of the intervention (45 min. twice a week for eight weeks) were chosen because prior balance exercise intervention studies with a similar timeframe achieved significant changes in balance, and the intervention could be feasibly replicated in clinical practice. The intensity of the intervention (moderate to high challenge with infrequent rests) was chosen to require the attention and effort necessary to produce motor learning.

Exercise task and environmental condition variations to increase the difficulty level of the exercises. The exercises were progressed by modification of the following:

(1) *Stance position*: feet apart, together, staggered, tandem and single leg. Stance position was modified to induce greater instability and heighten the demand for sensory information.

(2) *Head position/motion*: e.g., head tilts, nods or rotations, uni-planar then multi-planar. Nods and rotations were initially slow but became faster as the participant improved. Head position and motion were manipulated to complicate reliance on vestibular inputs and prevent visual fixation.

(3) A*vailability of vision:* eyes open versus closed. Vision is made unavailable to provoke greater reliance on touch and somatosensory inputs.

(4) V*isual surround motion*: stationary, predictable motion, or random motion. Motion amplitude was progressed from small to large. Vision is made less useful or accurate to provoke greater reliance on touch and somatosensory inputs. Unlike eyes-closed challenge, visual motion cues that are non-stationary or inaccurate require central recognition and suppression. (5) A*vailability of touch/somatosensory information*: fingertip touch on a stable base, progressed from bilateral (walker) to unilateral (quad cane) to none; firm standing support surface or compliant foam pad progressing from 1" to 5" thickness. Touch is made unavailable and somatosensation is made inaccurate to provoke greater reliance on visual inputs.

(6) *Support surface motion*: stationary, predictable motion, or random motion. Motion amplitude was progressed from small to large. Somatosensation is made inaccurate to provoke greater reliance on visual inputs. Surface motion cues that are non-stationary or inaccurate require central recognition and suppression.

(7) *Concurrent manipulation of vision, touch and somatosensation cues:* Vision availability or visual surround motion, and touch availability, somatosensory accuracy, or support surface motion were concurrently manipulated to provoke greater reliance on vestibular inputs.

(8) *Target size*: large to small. Target size was reduced to increase task constraints; the smaller the target, the more difficult it was to control sway within the target bounds.

No home exercises were given. Participants could continue any longstanding exercise program, but were asked not to begin any new exercise during the 16 weeks of the study.

Extrinsic visual feedback to help participants discriminate 'sway' versus instability. Initially, continuous and immediate COG visual feedback was provided. That is, participants who were attempting to remain still observed a cursor [on a monitor] that moved as they swayed; this feedback was initially provided *during* the practice trial to show the participant where they were in space, in what direction and at what velocity they were swaying. This information helped participants' recognize when corrective shifts were needed (or not), and scale corrective shifts to match the need induced by excessive sway. Over the first four weeks of balance training, visual feedback was increasingly delayed and provided only after one or more practice trials were completed and after the participant had been asked to verbally evaluate their own performance.

The duration of practice trials for any given exercise varied between 30 and 180 s depending on the difficulty of the exercise and the endurance of the participant. Delays in the provision of COG visual feedback might be as short as 30 s or as long as several minutes, with delay duration increasing over time as the length and/or number of practice trials increased. Prior to viewing the delayed feedback, participants were asked to describe their self-perceived performance to the PT/PTA. After viewing the delayed feedback, the PT/PTA would ask the subject to summarize salient characteristics of the performance, providing correction if necessary. Following the feedback summary describing their actual performance, participants were asked to compare their perceived versus their actual performance, and to decide how they might be able to improve their performance prior to resuming practice. In this manner subjects were "weaned" away from the extrinsic visual feedback, and the use of their own intrinsic sensory feedback was facilitated. Visual feedback was very rarely provided during the second half of the exercise program.

Who

The exercise intervention was provided by one PT and two PTAs ('trainers') who were blinded to all test results. All trainers had greater than 2 years of clinical experience with older adults. They were trained in the use of the equipment, and the progression protocol, by one author who is a PT with multiple years of experience using the equipment and training other clinicians to use it. Whenever possible, trainer-participant pairs worked together consistently over the eight weeks.

How and Where

All exercise sessions were individual and delivered in-person, face-to- face, in the outpatient PT department of the large congregate retirement community.

When and How Much

Each participant completed two exercise sessions per week (Monday/Wednesday or Tuesday/Thursday) for eight weeks, a total of 16 exercise sessions. Each session was 45 minutes in duration. During the first four weeks, participants took one required 5-min seated rest approximately halfway through each session. In addition, participants were allowed to sit and rest whenever they requested, however, they were educated that they should rest only when necessary, and that time spent resting would not lead to improvement in balance. Trainers were educated to encourage a short, seated rest if participant performance began to deteriorate.

Some session time was also spent standing (but not exercising) after an exercise was completed to briefly review the participant's performance (shown on screen) before going on the next exercise; see above for detail.

We did not measure actual minutes spent exercising vs. reviewing vs. resting. The total number of minutes per session spent exercising depended on participant tolerance.

The exercises were not physically strenuous in the sense of aerobic endurance or resistance training, but did demand prolonged standing with a high level of attention and effort. Some participants did report temporary fatigue after the sessions that resolved by the following day.

Tailoring

The intervention protocol was the same for all participants, but the level of difficulty was personalized, as it would be in clinical practice. In other words, the intervention protocol spanned a wide spectrum of challenge levels, and each participant's starting point on that spectrum was individualized. Once started, the progression was similar in content but varied in rate, depending on how rapidly each participant improved.

For each participant, initial levels of difficulty were selected based primarily on the SOT® test results of that participant. During the SOT®, participants stand for multiple 20 second trials with feet apart and eyes open or closed depending on test condition. The surface (and visual surround) motion is sway-referenced in a 1-to-1 ratio with participant sway, which is similar [but not identical to] to the "100%" difficulty level set by the operator during training with surface (or visual surround) motion. If one or more of the SOT® conditions was easy for a participant, the initial exercise levels would be made more difficult than that condition. Conversely, if one or more of the SOT® conditions was difficult for a participant, the initial exercise levels would be made less difficult than that condition. For example, if a participant did very well on SOT® Condition 2 (eyes closed on a stable surface), any exercise on a stable surface with eyes closed might begin with feet together or in-tandem (vs. apart), and/or with head tilt or head motion (vs. head upright or still). If that participant did poorly on SOT® Condition 5 (eyes closed on a 1-to-1 sway-referenced surface), any exercise on a moving surface with eyes closed might begin with fingertip touch on a quad cane (vs. no touch), with the surface motion set at Predictable (vs. sway-referenced), and with dampened surface motion at 50% difficulty level (vs. approximately 100%).

For any given exercise, the difficulty level was increased as soon as the participant was successful at that exercise in approximately 75-80% of tries. For example, if, in a given stance position, a participant was able to keep their postural sway within a large target for 45 seconds with the surface motion difficulty set at Predictable:50% and the visual motion difficulty set at Random:30%, the exercise would be made more difficult by increasing the surface motion difficulty to 60% until successful, then increasing the visual motion difficulty to 40% until successful, then reducing target size to medium until successful.

Modifications

The intervention was not modified during the study.

How Well (Adherence)

Exercise schedules were planned in advance by one author with participant involvement. Participants could choose a Monday/Wednesday or Tuesday/Thursday schedule; if a session was missed, Fridays were 'make-up' days. Each participant came at the same time on their exercise days.

Individual written appointment calendars were provided. A master appointment calendar with all participants was kept, and a copy of it provided to the department receptionist. During the first two weeks, participants were telephoned on Sunday evening to remind them of their appointments that week. If a participant was late for an appointment, they received a telephone call to remind them of, or re-schedule, their appointment. Attendance was recorded using the individual participant tracking sheet described above.

Thirty-three older adults qualified for inclusion in the intervention program, 28 of them began the intervention, and 21 of them completed all 16 sessions. Of the 13 participants whose data are not included in the final analysis, six dropped out because of health status changes, and four due to caregiver burden. These factors were outside the control of the study. One participant decided to begin another (group) exercise program with a friend, while another participant dropped out because she did not enjoy the exercises. Data from one participant who completed the exercises was unusable following computer file corruption. For the 21 participants who attended all 16 sessions, the intervention was delivered as planned.

Appendix 4
Laboratory Multi-sensory Reweighting Protocol and Measures

What is MSR and how is it measured?

Visual, vestibular and somatosensory inputs are needed to maintain balance. Each of these three individual sensory inputs is ‘weighted’, or prioritized, during the central nervous system integration process. The resultant single perception of the body in space is the outcome of a ‘weighted sum’ of these multiple sensory cues. The ‘weight’ assigned to a given sensory input will decrease if environmental conditions render that sense relatively unavailable (e.g., vision is unavailable in darkness), inaccurate (e.g., somatosensation is inaccurate when walking on sand dunes), or irrelevant to the task at hand (e.g., an airborne skateboarder cannot use somatosensation to orient to the ground). Simultaneously the ‘weights’ assigned to the remaining available and accurate senses will increase. This dynamic multi-sensory re-weighting process ensures that the estimation of body position and motion in space is based on the most available, accurate and relevant sensory inputs. Multisensory reweighting allows us to maintain balance as environmental conditions change.[8-11]

Because MSR is a central nervous system process, it cannot be measured directly. It is measured indirectly by quantifying changes in postural sway that occur when environmental sensory stimuli, such as surface motion or visual motion, are manipulated. In this study we operationally defined MSR as changes in postural sway gain values across different sensory conditions. Postural sway gain is a calculated value equal to the ratio of postural sway *at a specific frequency* to the sensory stimulus motion amplitude provided *at that frequency*.

In order to determine whether or not, or how much of, any postural sway changes were driven by alterations in specific, separate sensory inputs, we measured postural sway in the time domain (Figure 3), then converted postural sway data to the frequency domain (Figure 4) to allow the discrimination of postural sway responses to separate visual and touch/somatosensory stimuli. This was accomplished by providing two sensory input stimuli (e.g., visual motion and touch motion) at two different frequencies that are both within the range of typical human sway frequencies (0-3 Hz). When postural sway frequencies are examined, adaptive sway responses at the stimulus motion frequencies are observed (Figure 4). The inter-relationships of more than one sensory stimulus (e.g., vision and touch/somatosensation) can be studied because each stimulus is provided at a separate frequency (Figure 4).

Systematic amplitude variation of sensory stimuli leads to corresponding changes in postural sway gain (gain = ratio of postural sway response amplitude at the stimulus frequency divided by stimulus amplitude). Postural sway gain values reflect the degree to which the postural control system is influenced by a specific sensory input (e.g., touch gain values reflect body sway relative to touch motion stimulus, and vision gain values reflect body sway relative to visual motion stimulus). Changes in gain are interpreted as reweighting of sensory inputs.

If the postural control task is to stand quietly (hold still), as in this study, then reliance on sensory stimuli that are relatively more still (smaller motion amplitude) will be more beneficial than reliance on sensory stimuli that are relatively less still (larger motion amplitude). Reliance on somatosensation (measured as touch gain) will decrease as somatosensory inputs become less still (touch motion increases) while vision inputs become more still (vision motion decreases), and vice versa. Reliance on vision (measured as vision gain) will decrease as vision inputs become less still (vision motion increases) while somatosensory inputs become more still (touch motion decreases), and vice versa. Thus, quantifiable changes in touch gain and vision gain constitute our measures of MSR.

We also measured the amount of postural sway at all frequencies other than the two specific frequencies of the visual motion and touch motion stimuli; this residual sway is represented by two variables, position variability and velocity variability. If these measures do not change across conditions while the gain values do change across conditions, we are able to demonstrate that the changes in gain values were due to the frequency-specific sensory motion stimuli, not just an overall change in postural sway.

Descriptons of MSR dependent variables:

Gain. Gain is a ratio of the amplitude of the postural sway response at the driving stimulus frequency to the amplitude of the stimulus, and reflects the coupling of postural sway to the stimulus motion. Gain was computed as the absolute value of the transfer function. If the postural sway response and stimulus amplitudes at the driving stimulus frequency are the same, the gain will equal one. Relatively speaking, the higher the gain value, the greater the reliance on and response to the stimulus.

It is critical to measure gain because t*he pattern of change in gain across the five different sensory conditions reflects MSR.* That is, rising gain values reflect increased responsiveness to the sensory stimulus, and vice-versa. When the amplitude of a sensory stimulus motion is increased (i.e., that sensory input becomes less 'stable' and reliable), gain values decrease and the reliance on that sensory input is decreased [re-weighting, in this case down-weighting, occurs]. The terms 'vision gain' and 'touch gain' refer to COM gain relative to the visual stimulus and touch stimulus, respectively.

Phase. Phase is a measure of the temporal relationship between postural sway and stimulus motion that reflects how close in time the postural sway trajectory was to the sensory stimulus motion trajectory. Postural sway may lead the stimulus, in which case phase will have positive values, or lag behind it, in which case phase will have negative values.

It is important to examine the phase values to ensure that the motion stimulus trajectory and the postural sway trajectory were not excessively far apart in time, as this would affect the accuracy of the gain values. Phase was computed as the argument of the transfer function and converted to degrees. The terms 'vision phase' and 'touch phase' refer to COM phase relative to the visual stimulus and touch stimulus, respectively.

Position and velocity variability. 'Position variability' and 'velocity variability' are variables used to characterize all of the remaining postural sway (at frequencies other than the driving stimulus frequencies) that was not examined using gain and phase values. Position and velocity variability reflect the range of COM positions and velocities over time, respectively.

Position and velocity variability of postural sway are calculated as the standard deviation of the residual COM displacement and its derivative, respectively, after removal of the postural sway response at the stimulus frequencies (cf. Jeka et al., 2000). The residual COM displacement was computed by subtracting sinusoids corresponding to the COM Fourier transform at the touch and vision stimulus frequencies. The derivative of the residual COM trajectory was computed by finite differences using every fifth value of the trajectory, corresponding to a time step of 0.1 s.

The analysis of position and velocity variability permit a more confident interpretation of the gain data. If gain values *do* change across conditions but variability does *not*, then the changes in gain can be confidently ascribed to the changes in sensory stimulus motion amplitudes. If, however, position and velocity variability *also* change in a parallel pattern across conditions, then sway overall is changing – perhaps due to other influential factors besides the sensory stimuli. In that case we would not be able to attribute the changes in gain primarily and directly to amplitude changes in the sensory motion stimuli.

Appendix 5
Terminology

Amplitude spectrum (also ‘frequency domain graph’): a graph that shows how much of the signal lies within each given frequency band over a range of frequencies. See Figure 4 A-E.

Argument of the transfer function: the ‘input’ signal(s) to the mathematical function, e.g. the visual and touch motion oscillations.

Derivative: a mathematical measurement of how a function changes when the input to the function changes. For example, the derivative of position is velocity, and the derivative of velocity is acceleration.

Fall: any event where you landed on the ground or any other lower surface when you did not intend to be there.

Fall-prone: the term ‘fall-prone’ refers to individuals who are at high risk for future falls based on their history of repeated falls, or one or more falls resulting in injury requiring medical attention.

Fourier transform: a mathematical operation that transforms one complex-valued function of a real variable into another. Complex numbers have a real part and an imaginary part. Our gain and phase values are calculated using this method.

Frequency domain: the analysis of signals with respect to frequency rather than time. Our two input signals were the visual oscillations at 0.2 Hz and the touch oscillations at 0.28 Hz. Our output signal was the postural sway, which in humans standing quietly without environmental motion cues is typically between 0 and 0.1 Hz. See Figure 4 A-E.

Function (mathematical): a mathematical method to demonstrate the dependence between two quantities, one of which is known (e.g., visual motion oscillation ‘input’, an independent variable) and the other is the response (e.g., postural sway ‘output’, source of our MSR dependent variables gain, phase, and variability).

Gain: Gain is a ratio of the amplitude of the postural sway response at the driving stimulus frequency to the amplitude of the stimulus, and reflects the coupling of postural sway to the stimulus motion.

Near-fall: an unintentional incident in which you lost your balance and *would have fallen down* if you had not received support from some nearby object (such as a handrail or piece of furniture) or person. If you would have ended up on the ground without some external support, those incidents are classified as a “near fall”.

Phase: a measure of the temporal relationship between postural sway and stimulus motion that reflects how close in time the postural sway trajectory was to the sensory stimulus motion trajectory.

Position variability: a variable used to characterize all of the remaining postural sway (at frequencies other than the driving frequencies) that was not examined using gain and phase values. Position variability reflects the range of COM positions over time.

Residual COM displacement: The COM sway response at all frequencies other than the two stimulus frequencies, used here to calculate ‘position variability’ and ‘velocity variability’.

Sway-referenced: Control of the support surface motion or visual surround motion such that the sway of the participant is the input or drive signal, and the support surface or visual surround motion is matched to the sway of the participant in a one-to-one ratio.

Time domain: the analysis of signals with respect to time. For postural sway analysis, typical time domain variables would include peak amplitude, peak velocity, sway trajectory, etc. See Figure 3.

Transfer function: a mathematical representation of the relationship between the input (visual or touch motion) and output (postural sway) of a system.

Transform (mathematical): a pair of mathematical operators that converts a function or signal between the time and frequency domains.

Unexplained falls: falls that are not understandably caused by some large external force, such as being run into in the hallway by a scooter, or situations in which any person might be expected to fall, e.g., standing on a support structure that collapses.

Velocity variability: a variable used to characterize all of the remaining postural sway (at frequencies other than the driving frequencies) that was not examined using gain and phase values. Velocity variability reflects the range of COM velocities over time.