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Supplemental Data

Motion Aftereffects Transfer between Touch and Vision

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Supplemental Experimental Procedures

Experiment 1: Vision to Touch

Initial Training - Tactile Motion Exposure. Observers were first familiarized to the tactile device and the sensation of motion sweeps produced by the device. Successive rows or columns of stimulation were delivered (30 ms/bar, 33.3 Hz deflection frequency), producing tactile motion either up, down, left, or right across the finger pad. Two sets of 20 sweeps were presented, and the observer verbally reported the direction of the sweeps and was given feedback if incorrect. Observers were then given sweeps up and down that consisted of three tactile bars (row 1, 3 and 5) where the timing between the bars varied from -40 ms to 40 ms. Observers had to report the direction (up/down) of 20 random sweeps. Observers were given feedback, and were told that while the previous motion sweeps had been relatively unambiguous, the device was capable of generating sweeps that were very difficult to discriminate, and that such near threshold-level decisions were going to be presented for the remainder of the experiment.

Tactile Motion Baseline Blocks. First, the tactile motion point of subjective equality (PSE) was measured without any visual motion prior to the stimulus. Observers completed 3 staircases, blocked, to familiarize them with the task. Further, these baseline blocks were used to estimate their tactile PSE baseline. Results of the staircase are shown in Supplementary Figure 1. There was no significant bias in the tactile PSE baseline, though pilot experiments indicated a slight bias to feel stationary ambiguous tactile stimuli as downward motion. The initial inter-stimulus-interval (ISO) for each staircase was always 1 ms.

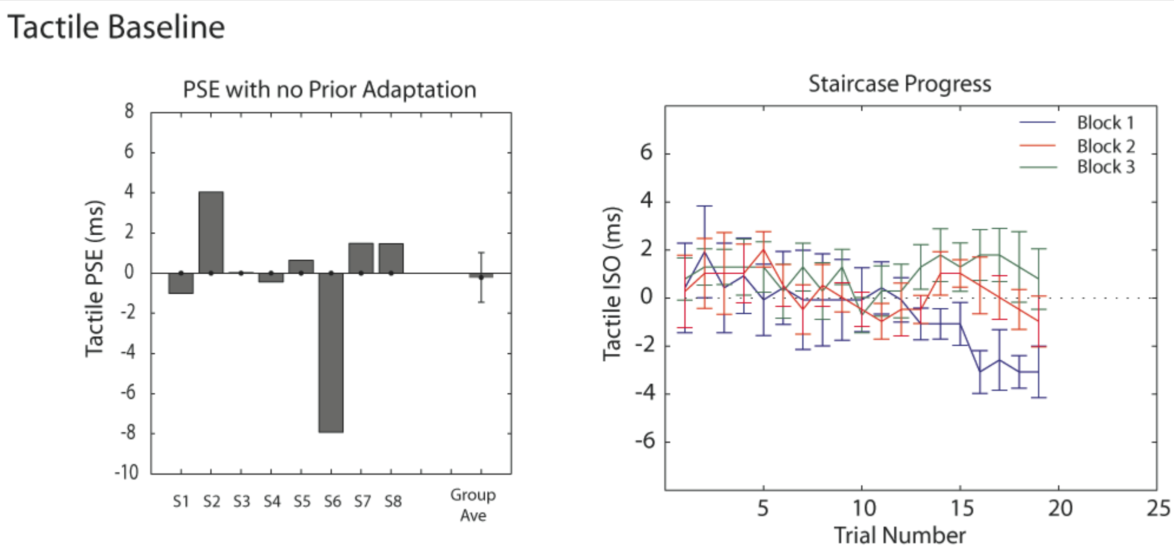

Figure S1. Tactile Baseline. Left: Average point of subjective equality for the tactile stimulus with no prior adaptation, for each participant and the group average. Right: average staircase progress for the three tactile baseline blocks. Error bars reflect within-subject standard error of the mean.

Experiment 2: Touch to Vision

Initial Training - Tactile Motion Exposure. Observers were familiarized to the device and presented with tactile motion sweeps (up/down/left/right, 30 ms/bar, 33.3 Hz deflection frequency, as in Experiment 1). Two sets of 20 sweeps were presented, and the observer verbally reported the direction of the sweeps and was given feedback if incorrect.

Tactile Visual Synchronizing Procedure. Next, observers were presented with the same tactile sweeps, 1 per second, randomly from among 4 directions (up/down/left/right), for 20 sweeps. At the same time as the tactile sweeps, a "matched" visual grating was presented which moved in the same direction, with the same onset and offset in time (1.9×2.3 degrees, with 10% Michelson contrast, a spatial frequency of 1.05 cycles per degree and a temporal frequency of 2 Hz, updated at a 60 Hz monitor refresh rate). Observers were told to observe the visual and tactile sensations and to imagine their finger aligned with the fixation dot.

Visual Baseline. The visual motion point of subjective equality (PSE) was first measured without tactile motion presented prior to the stimulus. The same staircase procedure described in the main text was used. Observers completed 3 staircases, blocked, each with a different starting phase jump (downward motion energy, upward motion energy, or no directional motion energy). Results of the staircase are shown in Supplementary Figure 2. There was a significant bias in the visual PSE baseline, with observers having a strong tendency to perceive the low-contrast counter phase flickering grating going downward (mean PSE = 16.4 degrees, S.E.M = 3.8 degrees, $t(7) = 4.38$, $p < .001$).

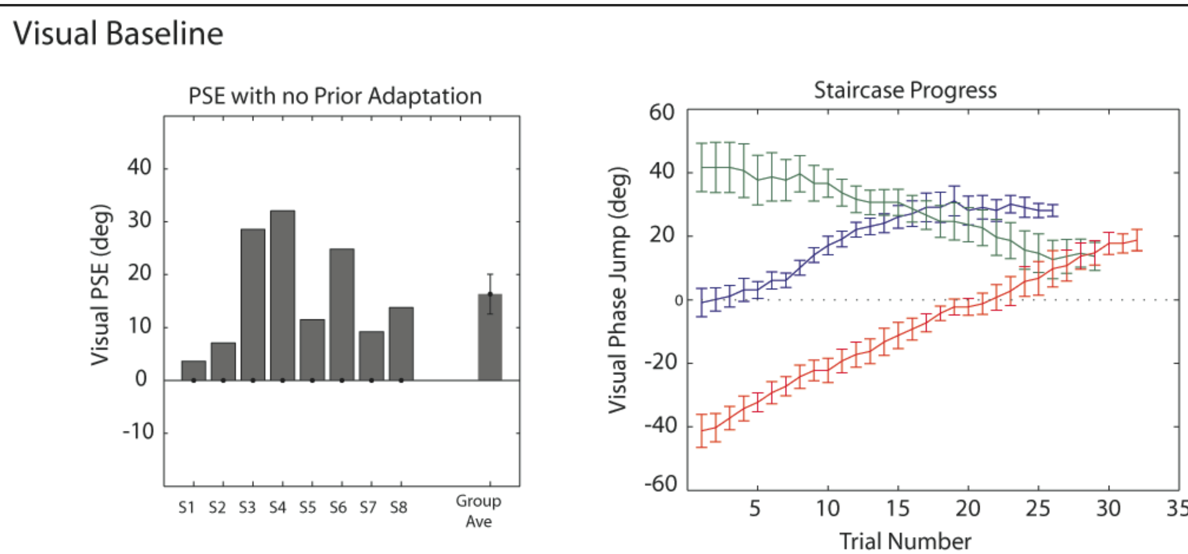

Figure S2. Visual Baseline. Left: point of subjective equality for visual motion with no prior motion adaptation, shown for each participant and the group average. Right: average staircase progress across subjects for the three baseline blocks. Error bars reflect within-subject standard error of the mean.

Supplemental Analysis: Alternate Calculation of PSE. As referred to in the main text, we conducted a supplemental analysis in which we varied the number of reversals that are used to calculate the PSE. Due to the visual baseline bias, any early reversals might obscure the relative differences between tactile motion adaptation up (or down) and baseline conditions with no adaptation. To address this we analyzed the component aftereffects (up vs. baseline; down vs. baseline), where the PSE for each subject and each condition is calculated as the average of the last 1, 2, 3… 10 reversals. The summary of this analysis is shown in Supplemental Figure 3.

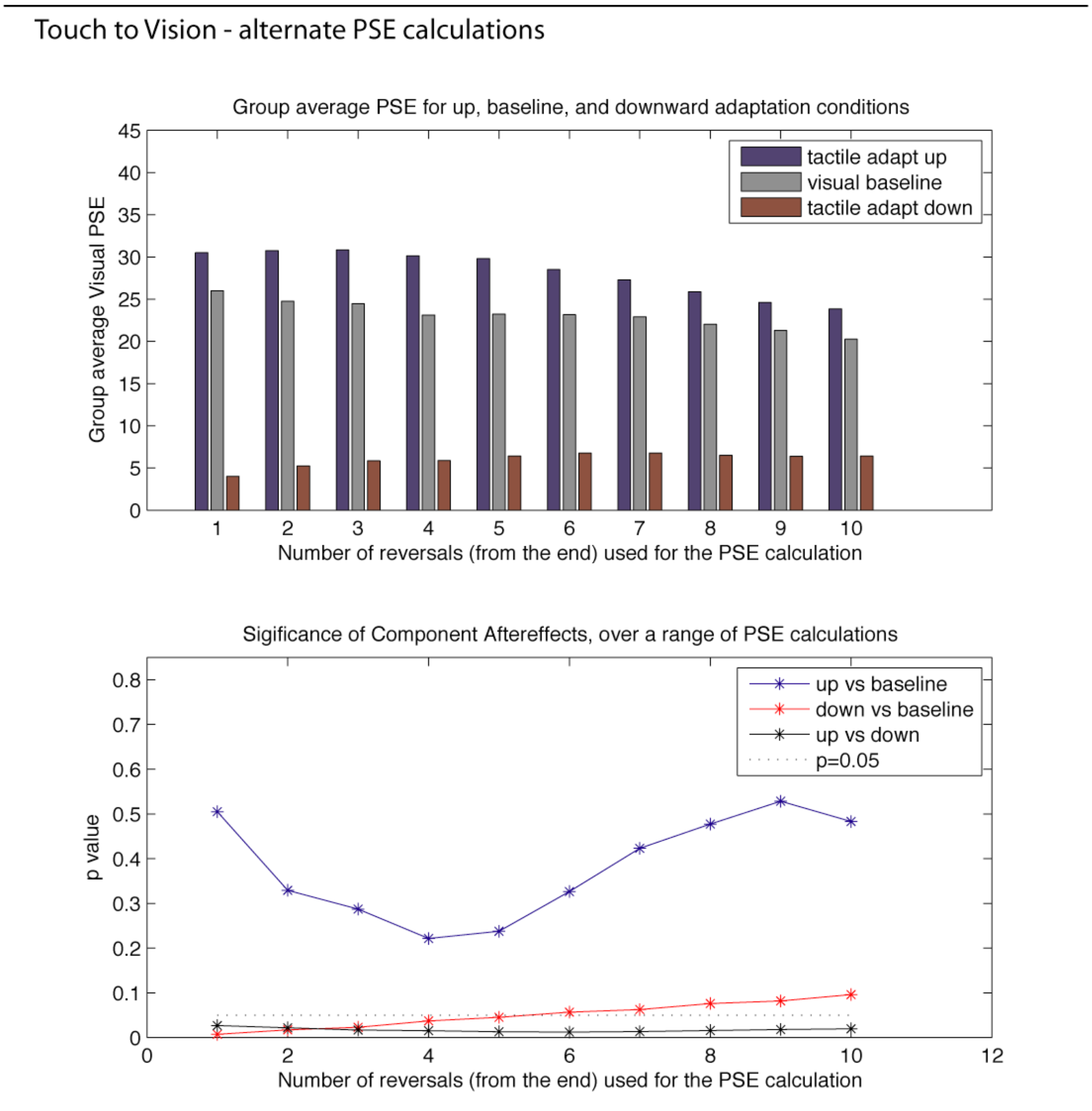

Figure S3. Alternate calculations of the PSE. Upper: Group average PSE for upward and downward adaptation and baseline conditions, as a function of the number of reversals used to calculate the PSE. Lower: Significance levels for the upward (red) and downward (blue) conditions, relative to baseline. Upward vs. downward significance levels are also shown (black).

Over a range of reversals included in the PSE calculation, the PSE shift following downward adaptation was relatively consistent. This PSE shift reached significance in cases where only the last 1 to 6 reversals were used to estimate the PSE, and was marginally significant when earlier reversals are included in the analysis. The PSE following upward adaptation is greater in magnitude when only the terminal reversals are used to calculate the PSE, as expected given that early reversals are more likely to be below baseline given the staircase seed. When comparing the PSE after upward adaptation to baseline, the component aftereffect nears significance when the last 4 to 5 reversals are used. Importantly, over the range of PSE calculations, the critical comparisons are stable. First, the average PSE after upward adaptation is greater than the average baseline PSE, which is greater than the PSE after downward adaptation. Second, the difference between upward and downward PSEs is significant across the entire range. These data further support the main results from experiment 2, namely that tactile motion adaptation systematically biases visual motion to be perceived in the opposite direction, a visual motion aftereffect.

Supplemental Experiment: Tactile Motion Aftereffects

To ensure the device and stimulation could produce tactile motion aftereffects following tactile motion, we piloted a range of tactile motion adaptation parameters. For six observers, a tactile adapting stimulus was played for 7.2 seconds, followed by a one second gap, and a static tactile bar test stimulus. The adapting stimuli could be one of 8 different sweep speeds (6, 10 12, 20, 24, 40, 48, 60 mm/sec) at 1 of 2 different deflection frequencies (20 Hz, 33.3 Hz). In this experiment, the tactile motion sweeps always were either leftward or rightward motion across the figure pad. The test stimulus was a static tactile bar (column 5) at the same local frequency as the adapting stimulus. Observers made a 2-alternative forced choice response as to whether the (stationary) test bar moved to the right or to the left. The experiment consisted of 10 trials per condition, in randomized order.

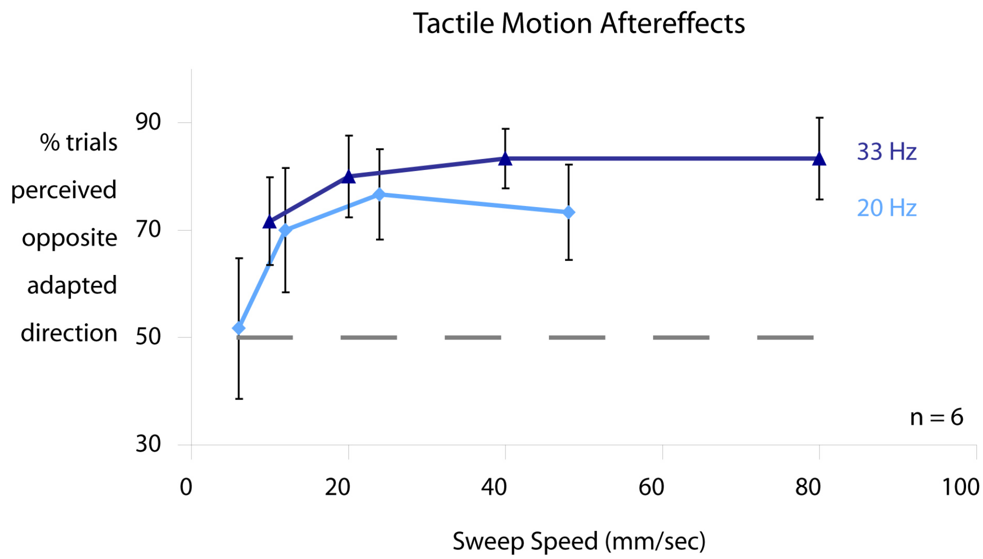

Figure S4. Evidence for robust tactile motion aftereffects following tactile motion adaptation. The sweep speed (mm/sec) is along the x-axis, with separate lines for the 33 Hz (dark blue) and 20 Hz (light blue) deflection frequencies. The y-axis shows the percent of trials in which the direction of the stationary test bar was perceived opposite the direction of motion. Data points above the chance line indicate consistent motion aftereffects.

The results are shown in Supplementary Figure 4. The sweep speed is plotted along the x-axis with separate lines for the 20 Hz and 33.3 Hz deflection frequencies. The y-axis shows the percent of responses opposite the direction of the adapting stimulus, collapsing across left and right motion adaptation directions. Thus, anything above the 50% line demonstrates a tactile motion aftereffect. We observed consistent motion aftereffects for all speeds except the slowest speed (6 mm/sec) and for both local deflection frequencies. This demonstrates that robust tactile motion aftereffects can be produced given the present range of stimulation.

Supplemental Experiment: Verifying Visual Intrinsic Bias

In the baseline estimates for perceiving upward and downward visual motion, we observed a systematic bias for observers to see counter-phase 180 gratings as downward. To verify this, we tested 7 naïve observers, and measured the visual motion point of subjected equality (PSE) using a method of constant stimuli (rather than the staircase procedure used in the baseline and experimental blocks).

30 trials were completed for 7 different phase shifts (from -90 to 90) between successive frames of the visual grating (grating parameters as in Experiment 1). Participants reported the direction of 1s

visual grating in a 2-alternative forced choice task. A logistic regression curve function was fit to each participant's data, and the PSE was calculated as the phase jump required for the visual counterphase grating to be perceived 50% up and 50% down.

There was a strong and systematic bias to see unbiased visual counterphase flickering gratings as downwards. At this phase jump (0 degrees bias), on average 68% of trials were judged downward, as opposed to the expected 50% if there was no bias, $t(6)=3.19$, $p < 0.05$). All seven participants showed this systematic bias. To quantify the magnitude of the bias, we calculated the amount of upward visual motion (in degrees phase jump between successive frames) needed to null the prior bias and achieve 50% upward/downward percepts. The estimated PSE for each subject and group average is shown in Supplemental Figure 5. The average PSE in this experiment was 19.3 degrees (SEM = 5.4, $t(6) = 3.56$, $p < 0.001$, not significantly different from the reported PSE of 16.3 (SEM = 3.77) found with a different group of subjects and a different method of estimation.

This intrinsic bias to perceive low contrast counterphase flickering gratings as going downward has been previously reported by Ohtani and Ejima (1997). Using a similar stimulus and paradigm, they found a bias of a similar magnitude (~20 deg) for foveally presented stimuli. They also varied the position of this grating with respect to fixation, and found downward biases for stimuli presented left, right, and below fixation, but not above fixation. Further, no systematic biases were found with left/right counterphase flickering gratings. These results can be interpreted in an ecological framework in which, if an observer has a slightly downward gaze-angle with respect to the horizon, optical flow patterns will expose the central and lower visual fields to downward motion when the observer walks forward.

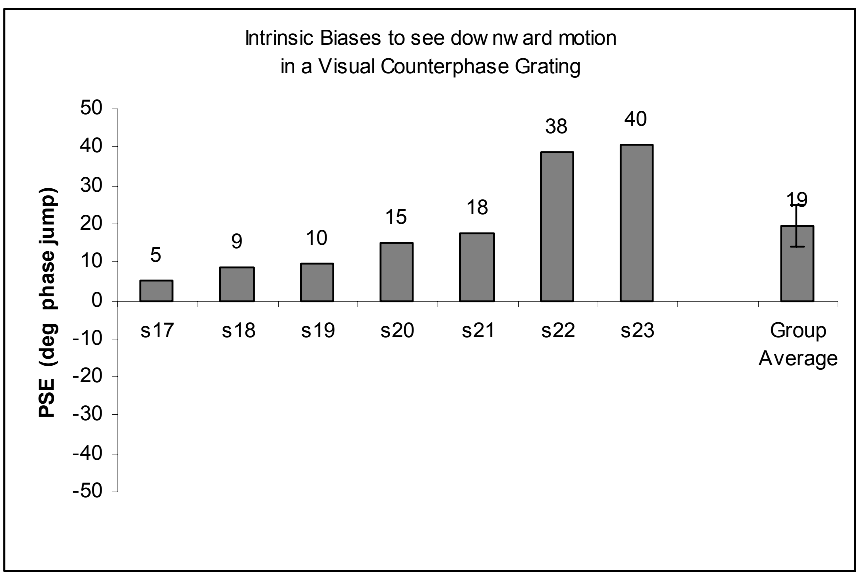

Figure S5. Point of subjective equality (PSE) for vertical visual counterphase gratings. The y-axis shows the degrees phase jump between successive frames, where 0 is a no-bias 180 degree counterphase flickering grating, positive values arbitrarily map to upward motion in the stimulus, and negative values map to downward motion in the stimulus. The estimated PSE, in which the stimulus is seen 50% up and 50% down is shown for 7 subjects and the group average. There is an intrinsic tendency to see visual motion downward, leading to a significantly upward shifted PSE.

References

1 Ohitani, Y., & Ejima, Y. (1997). Anisotropy for Direction Discrimination in a Two-frame Apparent Motion Display. Vision Research 37(6), pp. 765-767.