Supplementary Materials
Supplementary Figure S1: Data of all 106 subjects in Experiment 1, with each rectangle corresponding to one subject. Data from each of the two identical sub-sessions are shown separately. The border color of the rectangle reflects the results of statistical tests of the two bias types (blue: significant axial bias, orange: significant rotational bias, red: significant axial and rotational biases, black: neither significant). Subjects are ordered so that those with axial biases appear in the beginning, and those with rotational biases at the end.
Supplementary Figure S2: Full times series of all six subjects in Experiment 2. The 45 measurements for each subject (in the temporal order shown by numerals for the first subject) were over a period of 9 hours, and were taken at 12-minute intervals.
Supplementary Figure S3: Full times series of all six subjects in Experiment 3. The 45 measurements for each subject (in the temporal order shown by numerals for the first subject) were over a period of 9 hours, and were taken at 12-minute intervals.
A1 Auxiliary experiment: Temporal threshold for voluntary control

A1.1 Methods

The experiment was performed in the laboratory. There were two types of blocks: forced, where the subject was told which motion direction to attempt to perceive, and unforced, with no particular instructions.

A1.1.1 Stimuli

With the exception of the variable duration of the first frame, the quartet stimuli were identical to those in Experiment 2. The duration of the first frame was 200, 400, 600, 800 or 1000 ms, with the duration of the second frame fixed at 400 ms as in Experiment 2. As in Experiment 2, each block consisted of 24 trials, sampling stimulus orientations between 0° and 180°.

On forced blocks, the forced direction of motion (vertical, horizontal, clockwise or counterclockwise) was shown using a visual icon before the beginning of each block. Subjects were subsequently reminded of the forced direction using a verbal auditory cue before the start of each trial, the SOA between the auditory cue and the onset of the first visual frame being 700 ms. Before the start of unforced blocks, subjects were told that there were no particular instructions, and to just report what the motion that they saw; no auditory cues were given.

A1.1.2 Procedure

All conditions (motion direction to be forced, duration of first frame) were blocked. Each forced block was preceded by an unforced block.

The main part of the experiment consisted of 20 unforced-forced block pairs. Each of the 20 forced blocks has one of the four forced directions and one of the five initial frame durations. This factorial design was randomized, subject to the constraint that no two adjacent forced blocks have the same forced direction.

The main part of the experiment was preceded by the practice conditions, consisting of 4 unforced-forced block pairs. During the practice trials the forced direction on the first forced block was randomly chosen from clockwise or counterclockwise, while the direction on the second block was randomly chosen from vertical or horizontal, with the duration of the first frame equal to 1000 ms on both blocks. The second two forced blocks were the same as the first two, except with the duration of the first frame equal to 200 ms. Data from the practice conditions was not included in the analysis.

Thus, in total, the experiment consisted of 48 blocks. The blocks succeeded one another so that the each block began 4 minutes after the start of the previous block. Mean duration
of each block turned out to be about 70 seconds, so that subjects had, on the average, almost 3 minutes of rest between blocks.

A1.1.3 Subjects

Eleven naive subjects, none of whom participated in any other experiment in this study, took part in this experiment. They were paid 10€/hour.

A1.2 Results

The goal of this experiment was to measure the effectiveness of voluntary effort in modifying each subject’s individual bias pattern in the motion quartet. Using the data from the unforced blocks preceding the forced blocks, I took careful precautions to make sure that the underlying, unforced bias pattern immediately preceding the forced block was strong and stable. It was also important to exclude conditions in which the subject’s own bias pattern was being forced.

First of all, I excluded from further analysis subjects who had bias patterns that were weak or unstable during the 20 unforced blocks. There were 4 such unstable subjects, which left 7 subjects for the analysis. The dominant bias pattern of 6 of these subjects was vertical, and of the remaining subject counterclockwise.

Each trial of the remaining data was scored either 0 or 1 on four criteria: vertical, horizontal, clockwise and counterclockwise. For the clockwise and counterclockwise criteria, I simply used the responses (which were clockwise or counterclockwise). For the vertical and horizontal criteria, the trial was scored as 1 if the reported motion direction was within 45° of vertical or horizontal, respectively, and 0 otherwise. Taking the mean of these four scores yielded, for each block, four scores for verticalness, horizontalness, clockwise-ness and counterclockwise-ness.

Even in the 7 subjects with strong and stable biases, there were some fluctuations in the biases. I therefore found unforced blocks in which the mean score for the subject’s dominant bias pattern fell below 0.75. There were 13 such blocks out of a total of 140. Data from the forced block following these blocks were excluded.

Finally, it is meaningless to test the effectiveness of the instruction, say, to perceive vertical motion for a subject whose dominant bias pattern is already vertical. Therefore, all data where the forced motion was equal to the subject’s dominant bias pattern were excluded.

In the remaining data, for each forced block I calculated the mean criterion score for the forced motion, subtracting the same score from the preceding unforced block, considered as a baseline. For example, for a block in which the instruction was to perceive clockwise motion, I calculated the mean clockwise score (1 for clockwise responses, 0 for counterclockwise) for that block, and subtracted the same thing for the preceding unforced block. This yields an index for the effectiveness of the voluntary effort, positive if effective and zero otherwise.
Supplementary Figure S4: The results of the auxiliary experiment on the effectiveness of voluntary effort to perceive particular motion in the quartet. The horizontal axis represents the duration of the first frame of the quartet, while the vertical axis represents an index of the effectiveness of the voluntary effort, positive if the effort is successful (see text for definition). Dots show data for individual subjects, the solid line the mean over the subjects. Asterisks mark the durations of the first frame for which the effect of voluntary effort is significantly above zero.

The results are shown in Supplementary Figure S4, which displays the index for the effectiveness of voluntary effort as a function of the duration of the first frame. As can be seen in the graph, the effectiveness of voluntary effort rises with increasing first-frame duration. The slopes of the effectiveness versus duration are positive in 6 out of 7 subjects, with the mean slope significantly positive ($t_6 = 3.24, p = 0.02$). T tests for individual values of the duration revealed that the effectiveness is significantly positive for all durations greater than or equal to 400 ms, but not for 200 ms.

A1.3 Discussion

This experiment has shown that voluntary efforts to control the direction of motion of the quartet become less effective as the duration of the first frame decreases. At duration 200 ms, the effectiveness is close to zero and statistically no different from zero. This is in reasonable agreement with the observation of Ramachandran and Anstis that a cycling (rather than a single-shot) quartet becomes impossible to control voluntarily at temporal frequencies above 3 Hz. It is of course possible that subjects simply reported the direction of motion
we instructed them to attempt to perceive, rather than the direction of motion that they actually saw. This would artificially inflate the effectiveness, and therefore would decrease the temporal threshold of voluntary control. Thus, the 200-400 ms threshold found here should be thought of a lower limit on the actual threshold.