Action cost biases the perceptual decision making, only when the cost is implicit

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Perceptual decision is not simply determined by the incoming sensory input; it also reflects gains and losses that accompany decisions (Whiteley & Sanahni, 2008; Fleming et al., 2010). Although the result of decisions are usually expressed through action, it is yet unclear whether the effort to generate a response (motor cost) is incorporated into the perceptual decision making process. Here, we show that the motor cost associated with a particular perceptual choice can bias the human perceptual decisions when that cost is made implicit to the participants. Furthermore, we demonstrate that such shift in perceptual bias can transfer to the decisions performed through a different effector, which has not been associated with the motor cost.

Participants judged the direction (left or right) of a visual motion which was presented at different motion strengths. They judged the direction by moving a robotic device, which was held one in each hand. (i.e. leftward motion requires left hand movement) (Figure 1**a**). At the beginning (baseline condition), equal amount of resistance was provided to each of the hand (peak force; 8.8N). However, in the test condition, resistance further increased for left hand movements (peak force; 15.7N) (Figure 1**b**). In experiment 1 (n=10), resistance of the left hand increased by a small amount for every movement, so that the participants were not aware of the increased resistance. In experiment 2 (n=9), resistance increased in one single step, causing the participants to become aware of the manipulation.

Implicit increase of resistance to the left hand biased the visual perceptual judgment in a direction to avoid making leftward decisions (Figure 2**a**). However, this was not the case when the participants were aware of the cost (Figure 2**d**), even though the amount of additional motor cost was equivalent between the two experiments. To further examine the nature of this perceptual bias, the time to initiate the motor response (reaction time) in relation to the visual motion strength was analysed in a drift diffusion model framework (Hanks et al., 2006; Ding & Gold, 2012). Here, the decision is regarded as a result of accumulated evidence; when the evidence for a particular choice has accumulated sufficiently to reach a decision bound, the response is initiated. We found that the implicit motor cost biased the perceptual decision by changing the relative distances between the two decision bounds (heightening the level of evidence required for leftward judgement), without changing the evidence accumulation rate (Figure 2**c**).

Finally, we tested whether the implicit motor cost biases the perceptual decision at the level of the effector selection, or by the way of *reading-out* the visual motion information. Procedure of experiment 3 (n=12) was similar to experiment 1, except that the manual visual judgement task was interleaved with the non-manual task. The non-manual task required participants to judge whether the visual stimulus contains the coherent motion or not, by vocally answering “yes” or “no”. This allows us to estimate the sensitivity and the decision criterion for the two visual motions in a signal detection theory framework, without involving the hand. If the perceptual bias is due to the change in the decision representation upstream to the effector, the motor cost should also influence the non-manual task. We found that, even in the non-manual task, the perceptual decision was influenced by the prior exposure to the motor cost. Furthermore, resembling the pattern of result found in the drift diffusion model analysis, participants’ criterion to detect leftward motion became more conservative, without changing the sensitivity to the motion (Figure 3**b**, **c**).

Our result shows that the perceptual decision making is optimised to account for the implicit motor cost associated with the decision. Explicit knowledge about the cost may work as to avoid the integration between the irrelevant cost and the decision, to fulfil the primary objective of perceptual discrimination. Furthermore, the fact that the motor cost biases the perceptual decision at the level upstream to the independent effector control supports the embodied nature of our perception; *how we act constrains what we see.*

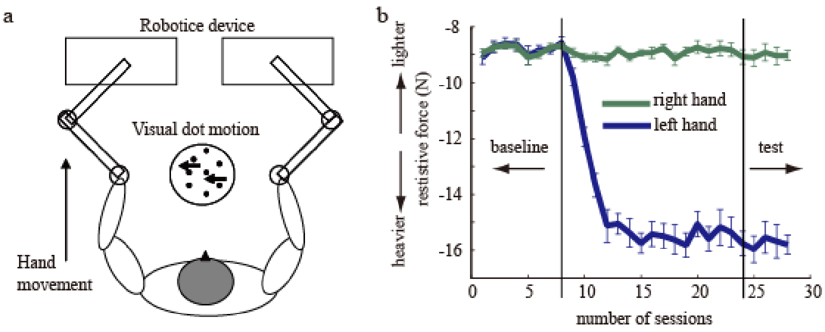

Figure 1. **a**: Setup of the experiment. Participants judged whether the random dot visual motion stimulus is either moving towards the left or towards the rigtht. The judgement was expressed by making a left hand reaching movement for leftward motion judgment, and right hand reach for the rightward motion. **b**: Amount of resitance (N) applied to the left and right hand movements. After the baseline condition, the resistance for the left hand increased. In experiment 1, it increased for small amount for every trial. In experiment 2, it immediately increased after the baseline condition.

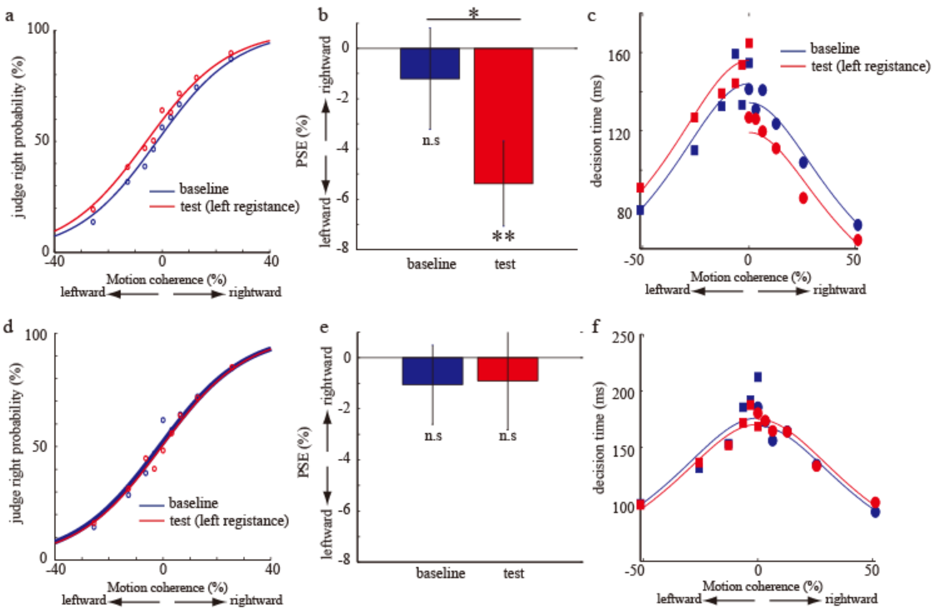

Figure 2. Result of experiment 1 (top three panels) and 2 (bottom three panels). The probability of choosing the rightward motion was plotted against the motion strength (psychometric function; **a**, **d**). The point of subjective equality (PSE; point of 50% judgement) calculated from the psychometric function shifted significantly towards the left (thus increasing the probability of judging the motion to be right) after exposed to the left hand motor cost for experiment 1 (**b**) (*p* < 0.05 vs. baseline), but not for experiment 2 (**e**). The reaction time of the decision was analysed by the drift diffusion model with 9 parameters for the fit (Ding & Gold, 2012); *k*: drift rate, *A* and *B*: decision bound for left and right choice, *Ta* and *Tb*: non-decision time for left and right decisions, *SV*: starting value difference for the bound value between baseline and test condition, *d_Ta* and *d_Tb*: difference in non-decision time between baseline and test condition, *d_coh*: additional coherent motion for test condition compared to baseline condition. Using these parameters, the chronometric functions [decision time (reaction time minus estimated non-decision time) plotted against the motion strength; **c**, **f**] were reconstructed. In experiment 1, after exposed to the motor cost on the left hand, the decision time became relatively slower for the leftward decisions, and faster for the rightward decisions (**c**). This was reflected as significant bias in the starting value ($p < 0.05$), but not for the evidence accumulation rate. This indicates that the motor cost made the decision bound of leftward decision to became relatively further, and the bound for the rightward decision to became relatively closer from the starting point, and induced a bias in the perceptual choice. This pattern of result was not observed in experiment 2 (**f**). * $p < 0.05$, ** $p < 0.01$

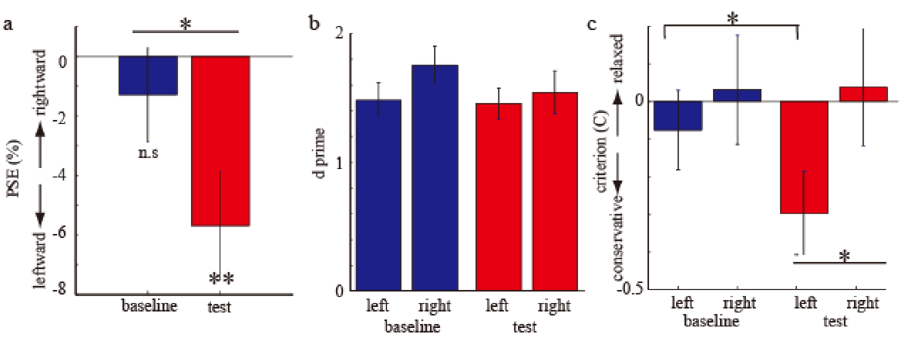

Figure 3; Result of exeriment 3. **a**: Result of the experiment 1 was replicated for the action task; probability to choose rightward motion (thus to avoid leftward motion) significantly increased. **b**, **c**: In the non-manual task, the motion sensitivity (d prime) did not change with the implicit motor cost (**b**). However, the analysis of the judgement criterion (C) showed that participants became more conservative to detect leftward motion after exposed to the motor cost, even though this non-manual task was done vocally without involving any hand movements. * $p < 0.05$, ** $p < 0.01$

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