Acquisition, representation, and transfer of models of visuo-motor error

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We examined how human subjects acquire and represent models of visuo-motor error and how they transfer information about visuo-motor error from one task to a closely related one. The experiment consisted of three phases. In the ***tr inin ph se***, subjects threw beanbags underhand towards targets displayed on a wall-mounted touch screen. The distribution of their endpoints was a vertically elongated bivariate Gaussian. In the subsequent ***choice ph se***, subjects repeatedly chose which of two targets varying in shape and size they would prefer to attempt to hit. Their choices allowed us to investigate their internal models of visuo-motor error distribution, including the coordinate system in which they represented visuo-motor error. In the ***tr nsfer ph se***, subjects repeated the choice phase from a different vantage point, the same distance from the screen but with the throwing direction shifted 45°. From the new vantage point, visuo-motor error was effectively expanded horizontally by $\sqrt{2}$. We found that subjects incorrectly assumed an isotropic distribution in the choice phase but that the anisotropy they assumed in the transfer phase agreed with an objectively correct transfer. We also found that the coordinate system used in coding two-dimensional visuo-motor error in the choice phase was effectively one-dimensional.

Introduction

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Isotropy bias

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Goals

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Figure 1. Experimental task and motivation. (A) The rationale for the choice task. Whether the subject's internal model of visuo-motor error distribution was vertically elongated, isotropic, or horizontally elongated should determine her choice between vertical and horizontal targets. Conversely, the subject's choices among different targets would allow us to make inferences about her internal model. (B) Training. On each trial, the subject threw a beanbag underhand to hit a target at the center of a wall-mounted touch screen. (C) Choice. The subject held a beanbag in her hand and stood either at the position where she was trained to throw (choice position) or at a new position that was the same distance from the screen but at a 45° viewing angle. On each trial, the subject saw a pair of sequentially displayed targets and was asked to verbally report whether the first or the second target was easier to hit, assuming she attempted the targets from where they stood. The subject did not throw the beanbag or receive feedback. (D) The objectively correct transfer from the choice to the new position. Suppose the standard deviations of the subject's visuo-motor error distribution on the screen are σ_x and σ_y. The geometric relationship between the choice and the new positions would determine the on-screen error distribution at the new position with standard deviations satisfying $\sigma_x^N \approx \sqrt{2}\sigma_x^C$ and $\sigma_y^N = \sigma_y^C$.

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(0°) σ_x^C σ^C,
(45°) σ_x^N σ^N,

$$\begin{array}{l} \sigma_x^N = \sqrt{2}\sigma_x^C \\ \sigma^N = \sigma^C \end{array} . \quad (1)$$

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3. Coordin te systems

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Estimating internal models

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Methods

Ethics statement

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Subjects

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Apparatus and stimuli

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Procedure and design

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Choice ph se

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Tr nsfer ph se

new position, ,

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Preanalyses for individual subjects

True visuo-motor error distribution

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300 20 15

. $(x, \ )$ i B_i

$$\phi_{B_i}(x, \ ) = \frac{1}{2\pi\sigma_x^{B_i}\sigma^{B_i}} \exp\left(-\frac{x^2}{2(\sigma_x^{B_i})^2} - \frac{^2}{2(\sigma^{B_i})^2}\right). \quad (2)$$

, 14%

5%

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$(x, \ )$ S.

E

$$f(E|\sigma_x^{B_i}, \sigma^{B_i}) = \begin{cases} \phi_{B_i}(x, \ ), & \text{if } E \text{ is on the screen} \\ 1 - \int_S \phi_{B_i}(x, \ ), & \text{if } E \text{ is outside the screen} \end{cases} \quad (3)$$

$\sigma_x^{B_i}$ σ^{B_i} -

.

$\sigma_x^{B_i}$ σ^{B_i} - t

$$\sigma_x(t) = \theta_x + \kappa_x e^{-\upsilon_x t}$$
$$\sigma \ (t) = \theta \ + \kappa \ e^{-\upsilon \ t}, \quad (4)$$

$\theta_x, \kappa_x, \upsilon_x, \theta \ , \kappa \ ,$ υ ,

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$t =$ $+ 15(i - 1)$.

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Subjects' intern l model of visuo-motor error distribution

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$$\psi(x, \ |\sigma_x, \sigma \ ) = \frac{1}{2\pi\sigma_x\sigma} \exp\left(-\frac{x^2}{2(\sigma_x)^2} - \frac{^2}{2(\sigma \ )^2}\right), \quad (5)$$

σ_x σ , σ_x^C σ^C

σ_x^N σ^N

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. T_1 T_2,

p_1 p_2

-

$$p_1 = \int_{T_1} \psi(x, \ |\sigma_x, \sigma \ )dxd \ ,$$
$$p_2 = \int_{T_2} \psi(x, \ |\sigma_x, \sigma \ )dxd \quad (6)$$

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T_2 $p_1 - p_2$

(, ,

, & , 2002)

$$\Pr(T_2) = \frac{1}{1 + e^{(p_1 - p_2)/(\tau D)}}, \quad (7)$$

$D = p_1(1 - p_2) + (1 - p_1)p_2$

$\tau > 0$

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$\tau, \sigma_x^C,$ σ^C (σ_x^N σ^N)

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Exclusion of subjects

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T_2

$$\Pr(T_2) = \frac{1}{1 + e^{(A_1 - A_2)/\left(\tau(A_1 + A_2)\right)}}, \quad (\ )$$

A_1 A_2 T_1 T_2

$\tau > 0$

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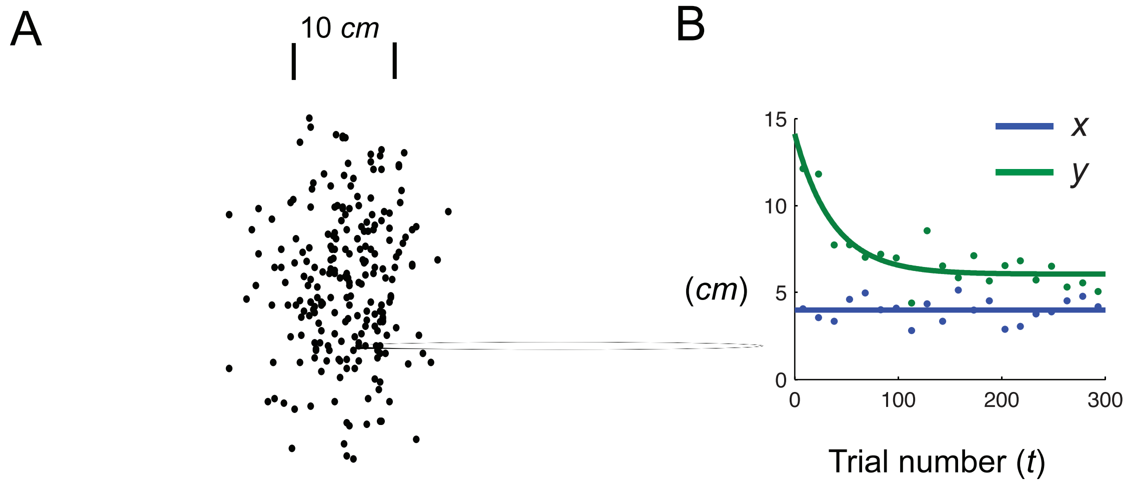

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- σ_x^C

σ^C (σ_x^N , σ^N)

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Results

True visuo-motor error distribution

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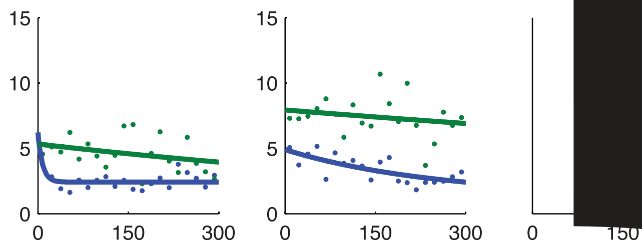
σ_x^T

σ^T (" ").

$\sigma^T = \sqrt{\sigma_x^T \sigma^T}$ - -



$\beta^T = \sigma^T/\sigma_x^T$.
t
σ_x^t, σ^t, σ^t, β^t.

$(\beta^T > 1)$.
(3), β^T
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Internal models at the choice and new positions

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(σ_x^C σ^C) ( )
(σ_x^N σ^N).
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Learning of the anisotropy estimate

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-4.0 , $p = 0.002$.
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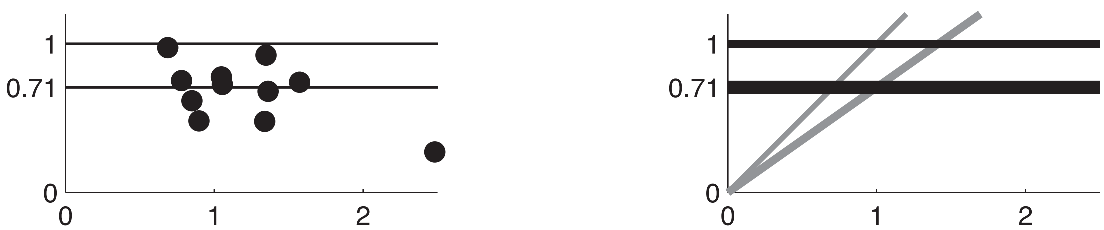

3 , - - 0.072. β^C β^t

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, . ., β^C - , - - ,
1 (- - t), $t(11) =$
1.12, $p = 0.2$. , -
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5 β^C β^T -
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β^C β^T
0.05 .
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β^C β^T, ' $r = 0.56$, $p =$.

Transfer of the anisotropy estimate

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$\beta^N = \beta^C/\sqrt{2}$. 5 , β^N
$1/\sqrt{2}$ (0.71),
β^C.
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$$
\begin{aligned}
&H_1 \quad \beta^N = 1/\sqrt{2} + \varepsilon,\\
&H_2 \quad \beta^N = 1 + \varepsilon,\\
&H_3 \quad \beta^N = 1/\sqrt{2}\beta^C + \varepsilon,\\
&H_4 \quad \beta^N = \beta^C + \varepsilon
\end{aligned}
\tag{9}
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β^N. H_1

(5 , 5)
, H_1 2
β^N
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H_1 1,321.
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Coordinate systems for visuo-motor error

σ_x^C σ^C
(, $r = 0.$, $p < 0.001$), σ_x^N σ^N
(, $r = 0.$ 2, $p < 0.001$), ,
σ_x^T σ^T $r = 0.5$, $p =$
0.04 (

$r = 0.62$, $p = 0.041$).
- σ_x^T σ^T
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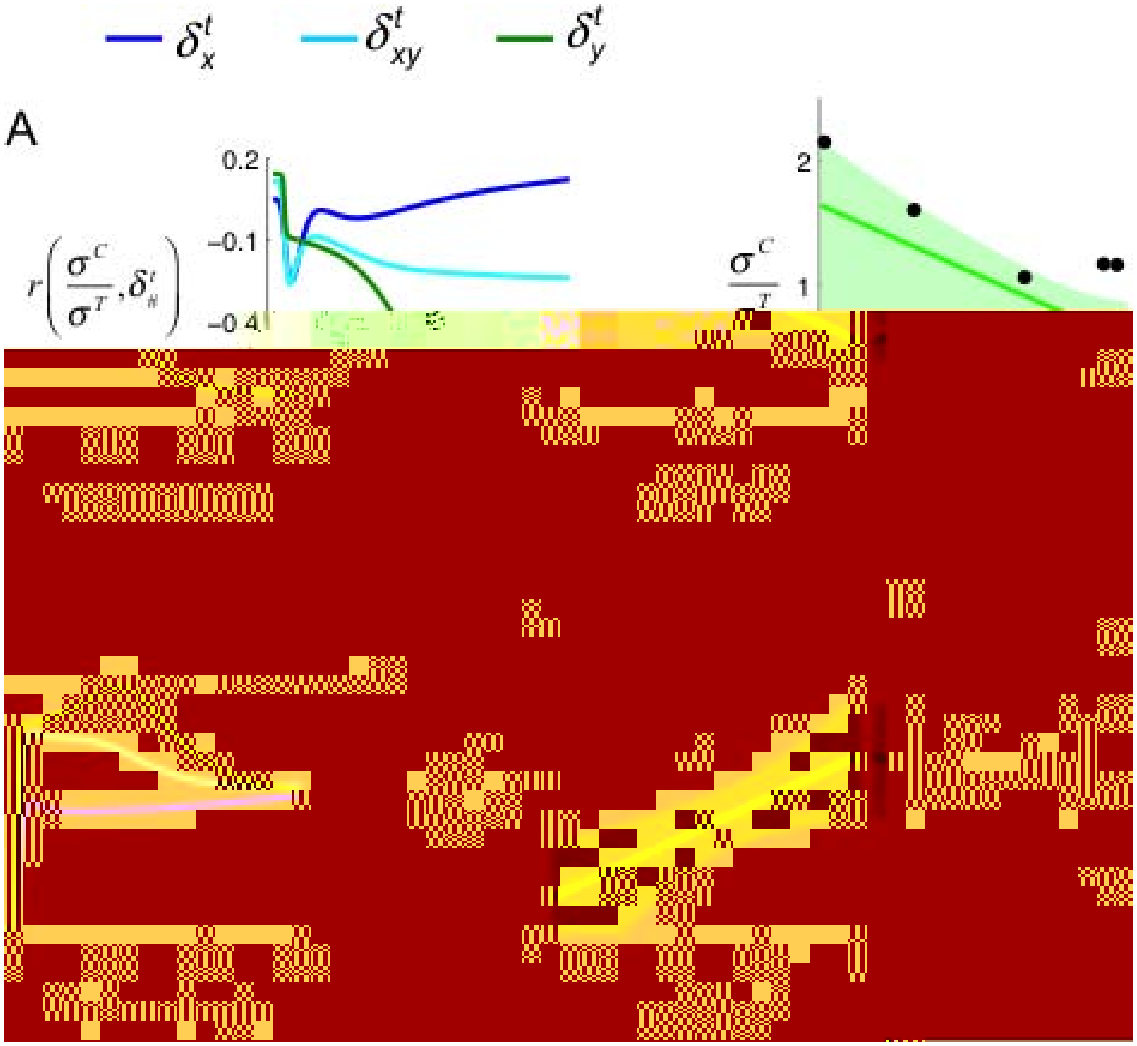

Figure 6. Standard deviations assumed in the internal model. The symbols δ_x^t, δ_y^t, and δ_{xy}^t denote the change rate of true standard deviations at trial number t, respectively, for the horizontal direction, the vertical direction, and overall (i.e., $\delta_{xy}^t = \sqrt{\delta_x^t \delta_y^t}$). (A) Learning. Left: Pearson's correlation between the misestimation of true standard deviation at the choice position (σ^C/σ^T) and the change rates. The horizontal line marks the significance level of 0.05. The correlation was significant only for the vertical change rate (green curve) in the second half of the training phase. A 75-trial range of the most prominent correlations was from trial 225 to trial 300. Right: The correlation σ^C/σ^T predicted by $\sigma_y^{300}/\sigma_y^{225}$. Each dot denotes one subject. Solid line denotes the linear prediction. Shadow denotes its 95% confidence interval. (B) Transfer. Left: Pearson's correlation between the mistransfer of standard deviation from the choice position to the new position (σ^N/σ^C) and the change rates. The horizontal line marks the significance level of .05. The correlation was significant only for the vertical change rate (green curve) in the second quarter of the training phase. A 75-trial range of the most prominent correlations was from trial 85 to trial 160. Right: The correlation σ^N/σ^C predicted by $\sigma_y^{160}/\sigma_y^{85}$. Each dot denotes one subject. Solid line denotes the linear prediction. Shadow denotes its 95% confidence interval.

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Discussion

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The isotropy bias: Cognitive constraints

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Coordinate systems

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Ke words: perception and action, movement planning, visuo-motor uncertaint , representation, transfer, choice

Acknowledgments

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Appendix

Detailed results on the variance estimate

Le rnin of the v ri nce estim te

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. 6 , - σ^C/σ^T δ^t_x (δ^t, δ^t_x) t. σ^C/σ^T δ^t ($p < 0.05$). , t, σ^C/σ^T δ^t_x σ^C/σ^T δ^t_x ($p > 0.41$). 6 σ^C/σ^T σ^{00}/σ^{225}. σ^{00}/σ^{225} δ^t 225 300, 75- σ^C/σ^T δ^t. σ^C/σ^T σ^{00}/σ^{225} (σ^C/σ^T δ^t) ,

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σ^C/σ^t δ^t t (1 300). 5.

σ^C/σ^T δ^t

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Tr nsfer of the v ri nce estim te

$(\sigma_x^N = \sqrt{2}\sigma_x^C,$ $\sigma^N = \sigma^C),$ $\sigma^N = \sqrt[4]{2}\sigma^C.$ 6 $\sigma^N/(\sqrt[4]{2}\sigma^C)$ δ_x^t (δ^t, δ_x^t) t.

$\sigma^N/(\sqrt[4]{2}\sigma^C)$ δ^t ($p < 0.05$). t, $\sigma^N/(\sqrt[4]{2}\sigma^C)$ δ_x^t $\sigma^N/(\sqrt[4]{2}\sigma^C)$ δ_x^t ($p > 0.21$).

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6 $\sigma^N/(\sqrt[4]{2}\sigma^C)$ σ^{160}/σ^{85} (δ^t 75- $\sigma^N/(\sqrt[4]{2}\sigma^C)$ δ^t). ($\sigma^{160}/\sigma^{85} = 1$),

($\sigma^N/(\sqrt[4]{2}\sigma^C) = 1$).