Behavioral/Systems/Cognitive

Rule-Based Learning Explains Visual Perceptual Learning and Its Specificity and Transfer

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Visual perceptual learning models, as constrained by orientation and location specificities, propose that learning either reflects changes in V1 neuronal tuning or reweighting specific V1 inputs in either the visual cortex or higher areas. Here we demonstrate that, with a training-plus-exposure procedure, in which observers are trained at one orientation and either simultaneously or subsequently passively exposed to a second transfer orientation, perceptual learning can completely transfer to the second orientation in tasks known to be orientation-specific. However, transfer fails if exposure precedes the training. These results challenge the existing specific perceptual learning models by suggesting a more general perceptual learning process. We propose a rule-based learning model to explain perceptual learning and its specificity and transfer. In this model, a decision unit in high-level brain areas learns the rules of reweighting the V1 inputs through training. However, these rules cannot be applied to a new orientation/location because the decision unit cannot functionally connect to the new V1 inputs that are unattended or even suppressed after training at a different orientation/location, which leads to specificity. Repeated orientation exposure or location training reactivates these inputs to establish the functional connections and enable the transfer of learning.

Introduction

[illegible]

[illegible]

[illegible]

Materials and Methods

Observers and apparatus. [illegible]

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 0270-6474/10/3012323-06$15.00/0

T . . . . PC- . W V . . . (N . . - . . I .). G . . . . . 21- . S G520 . . (1024 × 768 . ; 0.37 × 0.37 . ; 120 H . ; 50 . / 2 .), . . . 21- . D P1130 . (1024 × 768 . ; 0.37 × 0.37 . ; 150 H . ; 41 . / 2 .). L . . . 8- . . A . . . E . . . V . .

Stimuli. T G . (G . . = 6 . , SD = 0.17 , . = 0.47, .) (F . 1*a*), . . (F . 1, 2). T . . 4 . (. = 17) . . T . . .

T . (F . 3*a*). . . A . H . (1997). S . 7 × 7 . (22.2 ×1.3 .) . 42.5 ± 3.9 . . 2 . T . . (F . 3*a*, .), . 16 . T . (SOA), . 7 × 7 . 90 .

Procedure. C . - . (2AFC) . I . + Δ . Δ .) . (92 .) . 600 . T . (.) . (.). T . 200 . 200 . T . / . E . 1 . (6.7 .), . SOA. T . (50% .). A . .

T . 79.4% . T . 0.05 . E . T . .

Results

Orientation specificity and transfer in orientation learning

W . S . (. ., W . ?) G . (F . 1*a*) . (36 126 , . Δ _ 1, . 1). A . 2, . -23 .

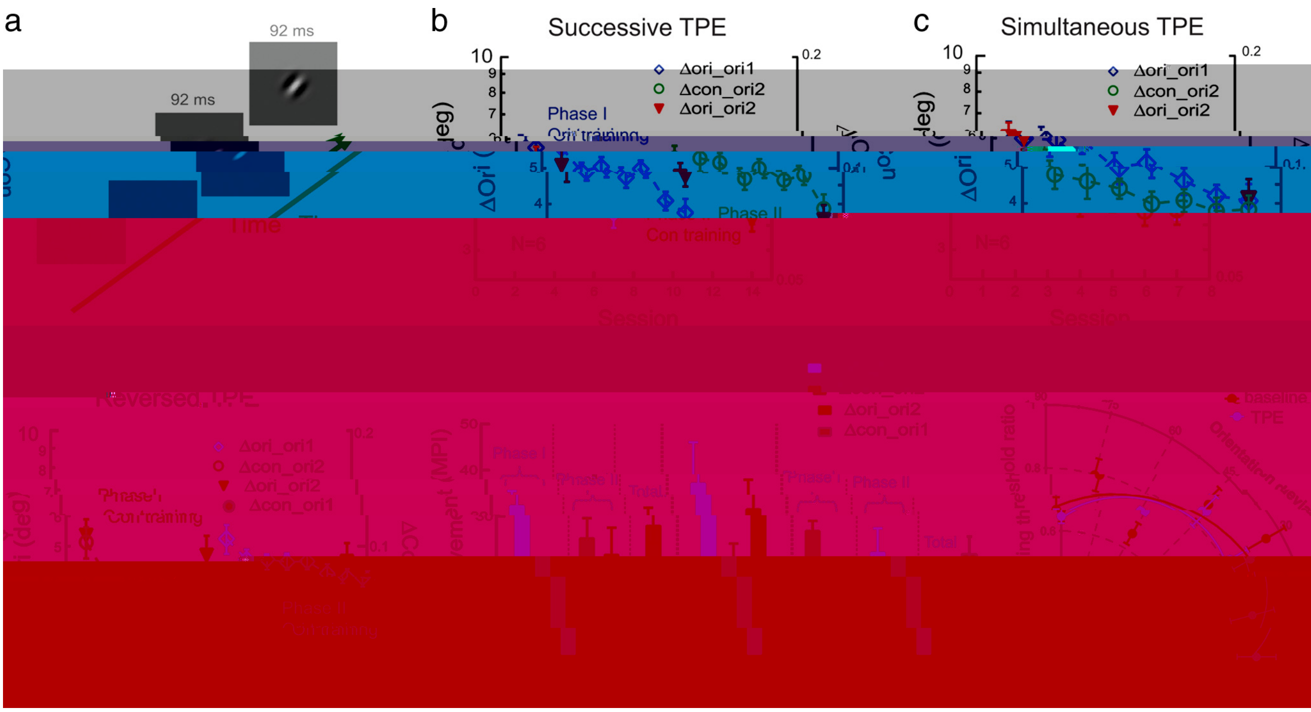

Figure 1. Perceptual learning of orientation discrimination and its transfer to a second orientation studied with TPE procedures. ***a***, The stimulus configuration for orientation discrimination in which one interval contained a more clockwise Gabor stimulus. ***b***, Successive TPE procedure. Phase I (sessions 1–7): orientation discrimination was practiced at one orientation (36°/126°, Δori_ori1, blue diamonds; orientation thresholds indicated by the left ordinate) and the transfer of learning was tested at an untrained orthogonal orientation (126°/36°, Δori_ori2, the left two red triangles), which replicated typical orientation specificity in orientation discrimination learning. Phase II (sessions 8–14): the same observers were later exposed to the transfer orientation ori2 in a contrast-discrimination learning task around the same transfer orientation (126°/36°, Δcon_ori2, green circles; contrast thresholds indicated by the right ordinate) and the transfer of orientation learning to ori2 was remeasured (126°/36°, Δori_ori2, the right two red triangles). Thresholds are averaged over all observers' data; error bars represent one SEM. The left and right ordinates have the same scale factor in log units. ***c***, Simultaneous TPE procedure: orientation discrimination was practiced at ori1 (Δori_ori1, blue diamonds) while the transfer orientation ori2 was exposed in a contrast-discrimination learning task (Δcon_ori2, green circles) and the transfer of learning was tested for orientation discrimination at ori2 (Δori_ori2; red triangles). ***d***, Reversed TPE procedure. Phase I (sessions 1–7): contrast discrimination was practiced around ori2 (Δcon_ori2; open green circles) and the change of orientation discrimination performance was measured at ori2 (Δori_ori2; left two red triangles). Phase II (sessions 8–14): orientation discrimination was practiced at ori1 (Δori_ori1; blue diamonds) and the transfer of learning was measured at ori2 (Δori_ori2; right two red triangles). The untrained contrast threshold at ori1 (Δcon_ori1) was also measured after the TPE procedure (solid green circle with black outline). ***e***, A summary of learning and transfer. Left, Successive TPE in ***b***; middle, simultaneous TPE in ***c***; right, reversed TPE in ***d***. ***f***, The average posttraining/pretraining threshold ratios at various orientation deviations from the transfer orientations (36°/126°) with conventional (red circles, fitted with a Gaussian peaked at 0° orientation deviation) and TPE training (blue circles, fitted with the difference of two identical Gaussians peaked at 0° and 90° orientation deviations).

2 (Δ _ 2; ± 10 G) (MPI = 26.9 ± 2.1%, $p < 0.001$) (F . 1*d*,*e*), (Δ _ 2; MPI = 7.7 ± 5.8%, $p = 0.083$).

I TPE (. ., 1 , 2.). . T, 1 (Δ _ 1; MPI = 22.2 ± 5.1%, $p = 0.004$) (F . 1*d*,*e*). H , Δ _ 2 (MPI = 5.0 ± 2.6%, $p = 0.053$) (F . 1*d*,*e*). T, TPE F . 1*e*. W . D .

R , TPE , 1 (Δ _ 1; MPI = 22.6 ± 3.6%, $p = 0.001$) (F . 1*d*,) Δ _ 2 ($p = 0.13$), . H TPE TPE . T,

TPE . H , Δ _ 1 TPE Δ _ 2 Δ _ 1, Δ _ 2 Δ _ 1. T, F . 2.

W TPE . F TPE 0°, 15°, 30°, 45°, 60° (36° 126°) . T 2. A . W TPE (F . 1*f*). B 30° TPE .

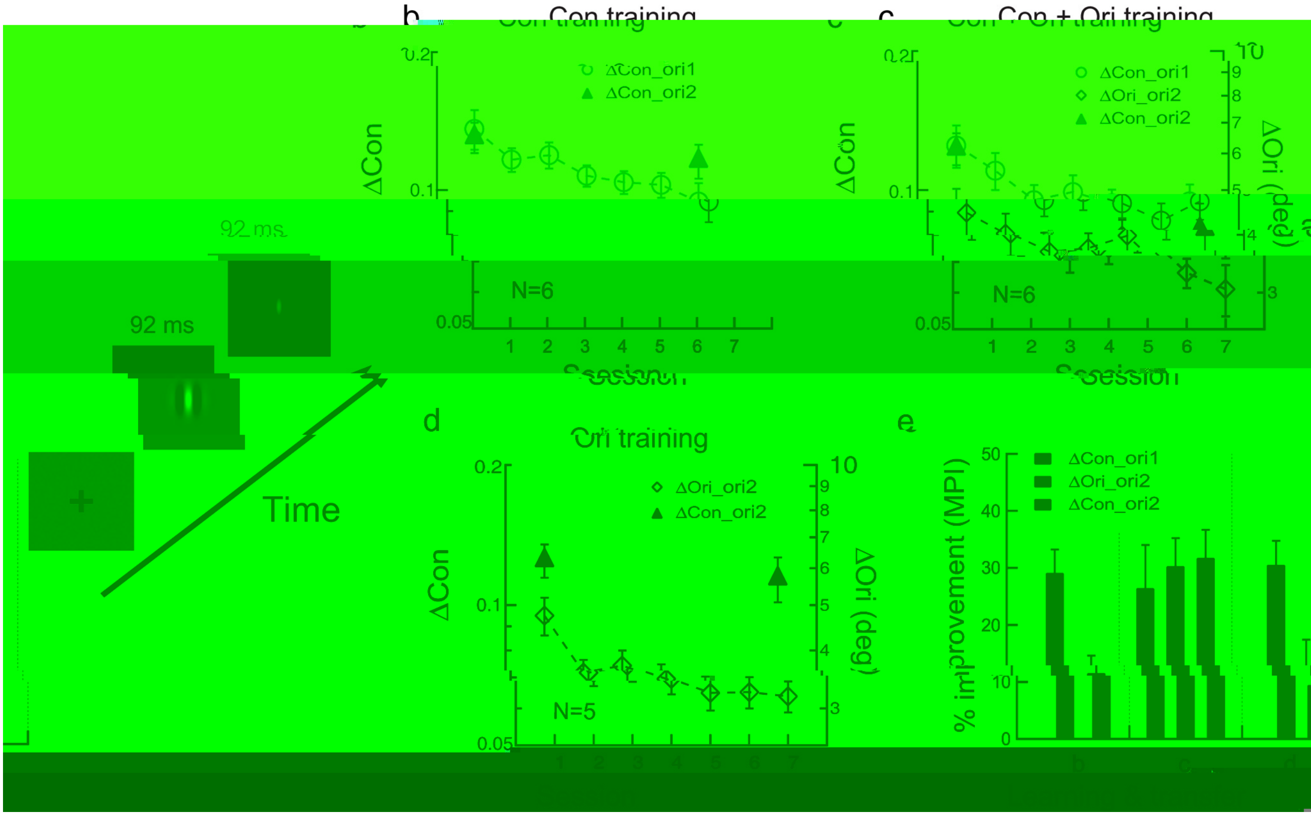

Figure 2. Orientation specificity in contrast learning studied with conventional and TPE procedures. ***a***, The stimulus configuration for contrast discrimination in which one interval contains a higher contrast Gabor stimulus. ***b***, Conventional training. Contrast discrimination for a vertical or horizontal Gabor was practiced (Δcon_ori1; green circles) and the transfer of learning was tested at an untrained orthogonal orientation (Δcon_ori2; red triangles). ***c***, TPE training. Contrast discrimination was practiced at ori1 (Δcon_ori1; green circles; contrast thresholds indicasby the left ordinate) and orientation discrimination (the exposure condition) was practiced at ori2 (Δori_ori2; blue diamonds; orientation thresholds indicasby the right ordinate) in alternating staircases, and the transfer of learning for contrast discrimination was tested at ori2 (Δcon_ori2; red triangles). ***d***, Control. Orientation discrimination was practiced at the transfer orientation (Δori_ori2; blue diamonds) and its impact on contrast discrimination was tested at the same orientation (Δcon_ori2; red triangles). ***e***, A summary of learning and transfer. Left, Conventional training in ***b***; middle, TPE training in ***c***; right, control in ***d***.

Orientation specificity and transfer in contrast learning

T… TPE … (Fig. 2). T… G… (e.g., W… ? … 2, … (Δcon_ori1; MPI = 29.1 ± 4.1%, $p < 0.001$) (Fig. 2*b*,*e*). T… (Δcon_ori2; MPI = 11.6 ± 3.0%, $p = 0.006$), … Δcon_ori2 … Δcon_ori1 ($p = 0.020$).

A TPE … ori1 (Δcon_ori1), … ori2 (Δori_ori2, …). … H… ori2, … A… ori2 … ori2, … 1. T… G… 30% … 67%, ±1 … 0.47 …

… ori1 (Δcon_ori1) … ori2 (Δcon_ori2) … (MPI = 26.5 ± 7.5% … 30.3 ± 4.9%, $p = 0.008$ … $p = 0.001$, …) (Fig. 2*c*,*e*). S… ori2 (Δcon_ori2) … (MPI = 31.8 ± 4.9%, $p < 0.001$), … TPE …

A… (Δori_ori2; MPI = 30.5 ± 4.2%, $p = 0.001$) (Fig. 2*d*,*e*) … (Δcon_ori2; MPI = 382± 8.0%, $p = 0.15$). A… TPE … (TI = 1.70) (Fig. 2*c*) … (TI = 0.49) (Fig. 2*b*) … (TI = 0.25) (Fig. 2*d*) … ($p = 0.010$, … ANOVA).

Orientation … specificity … detection learning

N… TPE … A… H… (1937, 2004). I… (Fig. 3*a*, …), … SOA. T…

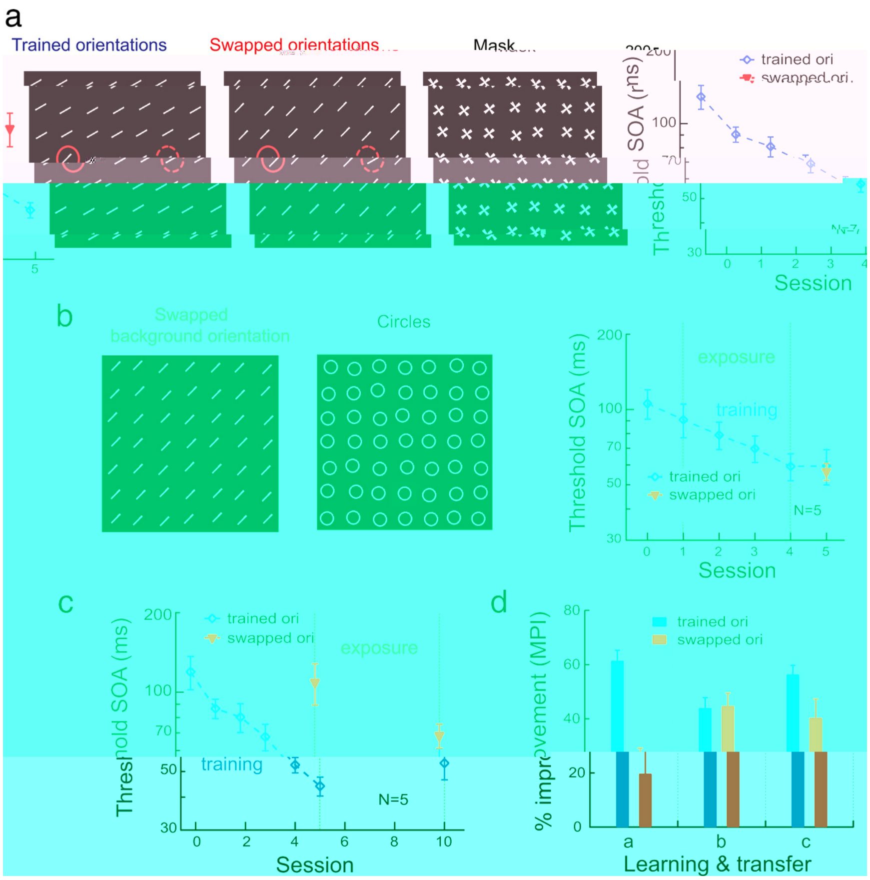

Figure 3. The effect of TPE training on transfer of feature detection learning across orientations. ***a***, Left three panels, Stimuli at trained target-distracter orientations (46° vs 30°), at untrained target-distracter swapped orientations (30° vs 46°), and the mask. The odd element (target) could appear at one of two positions (indicated by red circles that were not present in the actual stimuli). Right, Feature detection was practiced at trained target-distracter orientations (blue diamonds) and the transfer of learning was tested at swapped orientations (red triangles). The mean threshold over the first six staircase runs was taken as the baseline and is indicated by the 0th session. ***b***, Left and middle, Uniform stimulus array containing swapped-background orientation only or containing circles for the bars or circles judgment (the exposure condition). Right, Feature detection was practiced at trained target-distracter orientations (blue diamonds) and the swapped background orientation was repeatedly exposed (bars or circles) in alternating blocks of trials. The transfer of learning was tested at swapped orientations (red triangles). ***c***, The effects of later repeated exposure to the swapped-background orientation after baseline training in five observers from ***a***. ***d***, A summary of learning and transfer. Left, Baseline training in ***a***; middle, simultaneous TPE training in ***b***; right, successive TPE training in ***c***, in which the performance improvement was calculated by comparing the thresholds at the final 10th session and the 0th session.

3a, …). A … A … H … MPI … W … TPE … SOA (106.7 …). I … (… 80% …) (Fig. 3b, …) … (20% …) (Fig. 3b, …) … 60- … T … (MPI = 43.9 ± 3.9%, p < 0.001) … (MPI = 44.7 ± 4.8%, p < 0.001) (Fig. 3b, …). T … TI … TPE … (TI = 1.04) … (TI = 0.32) (p = 0.002, …). U … 8 … Fig. 3a … (…) … (Fig. 3c). F … (MPI = 9.6 ± 6.9%; p = 0.12) … (Fig. 3c, …). S … 33.9 ± 5.3% (p = 0.002) … (10th) … (Fig. 3c, …). T … MPI … 56.2 ± 3.4% (p < 0.001) … 40.3 ± 7.0% (p = 0.004) … (p = 0.12).

… (Fig. 3a, …). A … H … (1997) … (… 30 …). I … (… 16 …), … T … A … H … (A … H … 1997, 2004), …

W … A … H … (MPI = 61.4 ± 3.9%, p < 0.001, …) … (MPI = 19.7 ± 9.5%, p = 0.041) (Fig. …

Discussion

Existing models of perceptual learning predicting specificity, not transfer

T … (Fig. 1, 3) … (X … 2008; Z … 2010) … F … V1- … (A … 2002; T … Q … 2003; Z … 2003) … -V1 … (P … 1992; D … L … 1998). T … S …

(M… D…, 1996; L… G…, 2009). A … T… (J… …, 2009). A…

T… (F… 3), … (A… H…, 1997, 2004). R… H… TPE … (F… 3) … (D… L…, 2007) …

F… TPE … (F… 1b, 3c), … S… (S… W…, 2005).

A rule-based learning model

O… T…

Rule-based learning

E… V1 … H… F… V1 … G… T… V1 …

Rule application: specificity and transfer

O… T… W… V1 … (T…, 2001; V… S…, 2005; G…, 2009), … V1 … O… (F… 1, 3) … (X…, 2008) …

V1 … A… TPE … (F… 1d), … I… R… -…

W… F… W… I… ~200 … (Z…, 2010), … W… (S…, 1995).

References

A… Y, S… D, T… M (2002) C… N… 415:790–793.
A… M, H… S (1993) A… P… N… A… S… U S A 90:5718–5722.
A… M, H… S (1997) T… N… 387:401–406.
A… M, H… S (2004) T… T… C… S… 8:457–464.
D… BA, L… ZL (1998) P… P… N… A… S… U S A 95:13988–13993.
D… BA, L… ZL (2007) T… P… S… 18:531–539.
F… M (1994) H… P… 23:411–427.
G… V, K… LR, K… I, B… EM, S… JT, V… Z (2009) L… E… J N… 29:1723–1731.
J… PE, D… BA, P… A, L… ZL (2009) T… J V… 9:1–13.
K… A, S… D (1991) W… P… N… A… S… U S A 88:4966–4970.
L… CT, G… JI (2008) N… N… N… 11:505–513.
L… CT, G… JI (2009) R… N… N… 12:655–663.
M… JD, D… MV (1996) T… S… V… 10:51–58.
P… T, F… M, E… S (1992) F… S… 256:1018–1021.
S… AA, V… R, O… GA (1995) H… J P… 483:797–810.
S… A, W… T (2005) A… T… C… S… 9:329–334.
T… AF, Q… N (2003) L… V1 … J N… 89:2086–2100.
T… S (2001) N… T… N… 24:295–300.
V… Z, S… W (2005) L… V… R… 45:677–685.
X… LQ, Z… JY, W… R, K… SA, L… DM, Y… C (2008) C… C… B… 18:1922–1926.
Z… T, X… LQ, K… SA, L… DM, Y… C (2010) D… V… R… 50:368–374.
Z… L, H… MH, D… P (2003) N… N… 14:233–247.