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Unsupervised visual discrimination learning of complex stimuli: Accuracy, bias and generalization

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Through same-different judgements, we can discriminate an immense variety of stimuli and consequently, they are critical in our everyday interaction with the environment. The quality of the judgements depends on familiarity with stimuli. A way to improve the discrimination is through learning, but to this day, we lack direct evidence of how learning shapes the same-different judgments with complex stimuli. We studied unsupervised visual discrimination learning in 42 participants, as they performed same-different judgments with two types of unfamiliar complex stimuli in the absence of labeling or individuation. Across nine daily training sessions with equiprobable same and different stimuli pairs, participants increased the sensitivity and the criterion by reducing the errors with both same and different pairs. With practice, there was a superior performance for different pairs and a bias for *different* response. To evaluate the process underlying this bias, we manipulated the proportion of same and different pairs, which resulted in an additional proportion-induced bias, suggesting that the bias observed with equal proportions was a stimulus processing bias. Overall, these results suggest that unsupervised discrimination learning occurs through changes in the stimulus processing that increase the sensory evidence and/or the precision of the working memory. Finally, the acquired discrimination ability was fully transferred to novel exemplars of the practiced stimuli category, in agreement with the acquisition of a category specific perceptual expertise.

1. Introduction

Humans can discriminate an immense variety of sensory stimuli, ranging from highly dissimilar to highly similar exemplars. Although stimuli that differ in simple features are easily distinguishable, the discrimination of highly similar stimuli can be difficult or even unattainable. Visual sensory judgements are improved with practice up to "expert" levels of discrimination. Indeed, trained observers are able to rapidly distinguish subtle differences between stimuli or identify specific patterns, for example X-Rays (Boutis, Pecaric, Seeto, & Pusic, 2010) or cytopathological images (Crowley, Naus, Stewart, & Friedman, 2003; Evered, Walker, Watt, & Perham, 2013). In natural conditions, humans learn to discriminate complex visual stimuli through their daily experience in an unsupervised manner (Saffran & Kirkham, 2017). However, the majority of studies that have characterized visual learning in supervised conditions included explicit labels or/and feedback on performance, but see Tian and Grill-Spector (2015).

Sensory judgements are typically evaluated by the Signal Detection Theory (SDT) that distinguishes two independent components: the sensitivity and the criterion (Green & Swets, 1966). Usually, the effects of experimental manipulations on the sensitivity are attributed to changes in the perceptual process and the effect on the criterion to a decisional process. Interestingly, the manipulation of perceptual aspects of the task can have an effect on the criterion in certain conditions (Witt, Taylor, Sugovic, & Wixted, 2015). Thus, the effects on the perceptual processing are not exclusively associated to changes in the sensitivity as previously assumed. Alternatively, the performance has been evaluated in a model-free mode by the percentage of correct responses and the response preference that provides a measure of the predisposition to select among the response options.

The better performance of experts on discrimination of complex stimuli, measured as increases in sensitivity or accuracy, is attributed to

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the acquisition of a domain specific ability. A characteristic of the expert's discrimination is its generalization to the whole stimuli category. Moreover, the acquisition of this ability requires stimulus naming or categorization at the subordinate level and feedback on performance (Scott, Tanaka, Sheinberg, & Curran, 2006; Scott, Tanaka, Sheinberg, & Curran, 2008; Tanaka, Curran, & Sheinberg, 2005; Wong, Palmeri, & Gauthier, 2009), which together is defined as supervised experience or training. Alternatively, expert discrimination was obtained by the unsupervised identity training without labeling (Bukach, Kinka, & Gauthier, 2012) and a greater sensitivity and reduced incorrect responses to same and different pairs were obtained by unsupervised exposure to 3D stimuli (Tian & Grill-Spector, 2015). These results suggest that unsupervised training with stimulus individuation can lead to expert's levels of performance. In contrast, the unsupervised exposure to car models did not improve the sensitivity (Scott et al., 2008) suggesting that mere exposure is not sufficient for visual discrimination learning.

In addition to the sensitivity effects, visual learning may shift the criterion, typically associated to a decisional instead of perceptual process. A few studies have described contrasting results of criterion shifts. For example, unsupervised learning in a contrast discrimination and detection task with Gabor patches resulted in a shift in the criterion towards liberal values (Wenger, Copeland, Bittner, & Thomas, 2008; Wenger & Rasche, 2006). On the contrary, supervised discrimination learning in an auditory detection task reduced a bias in the criterion found in naïve observers (Jones, Moore, Shub, & Amitay, 2015). These contradictory results on criterion shifts may arise from differences in the feedback provided. Although feedback appears to be necessary for learning in perceptual tasks (Herzog & Fahle, 1997), it can also modify the sensitivity when provided block-wise (Aberg & Herzog, 2012) or induce a change in the criterion if observers receive a biased feedback (Herzog & Fahle, 1999). Accordingly, the feedback on performance may induce a response bias. Alternatively, a perceptual bias may induce criterion shifts (Witt et al., 2015). In consequence, the improvements in sensory judgements may involve shifts in the criterion with the consequent bias, in addition to improvements in sensitivity.

Same-different judgments are fundamental processes that take place during perceptual discrimination (Farell, 1985; Melara, 1992) and do not require a predefined feature or criterion for discrimination. The use of same-different tasks to compare the discrimination of naïve and expert observers has shown a reliably greater sensitivity for human movements in expert dancers (Calvo-Merino, Ehrenberg, Leung, & Haggard, 2010) and for cars models in car experts (Bukach, Phillips, & Gauthier, 2010). Supervised visual training with stimulus naming and categorization at the subordinate level, resulted in an improvement of sensitivity for birds (Tanaka et al., 2005) and car models (Scott et al., 2008). Because these studies were concerned with the modifications in the accuracy and sensitivity of experts, there were no explicit measures of accuracy for same and different trials individually or response bias. However, early perceptual studies with familiar stimuli showed a bias, characterized by more error with same pairs, in pitch discrimination (Coltheart & Curthoys, 1968) and simultaneous or sequential letter discrimination (Proctor & Rao, 1983). In contrast, no bias in the accuracy for same and different pairs was observed in the discrimination of sequential multi-letter pairs (Proctor, Rao, & Hurst, 1984). Additional studies of same-different judgements showed no bias on the accuracy for same and different pairs with familiar stimuli (flowers or human faces, accuracy > 0.9, Gauthier, Behrmann, & Tarr, 2004). However, a bias based on more errors on same pairs, was obtained with unfamiliar pseudo-Chinese characters (Chen, Bukach, & Wong, 2013). Moreover, supervised exposure to random viewpoints of unfamiliar 3D images resulted in a lower reduction of errors on "same" stimuli pairs (Tian & Grill-Spector, 2015), in agreement with a differential effect of training for same and different pairs. Overall, these results suggest that different levels of familiarity with the stimuli may modulate the relative errors on same and different pairs, and thus the occurrence of a bias in the response.

In conclusion, there is not enough evidence to demonstrate that visual discrimination learning equivalent to "expert" levels can be attained through same-different judgements of stimuli pairs in an unsupervised manner and how increasing grades of familiarity with stimulus patterns shape the performance for same and different pairs and the contribution of a bias in the criterion. To address this issue, we used a modified version of the same-different task where participants learned to discriminate complex visual stimuli in unsupervised conditions. In this study, we characterized the visual discrimination learning of two unfamiliar complex multi-exemplar stimuli categories. We evaluated if perceptual training was accompanied by shifts in criterion and response preference in addition to the increase in sensitivity and accuracy for same-different stimuli pairs while the observers acquired familiarity with the stimuli category. Moreover, we evaluated if perceptual training led to a generalization of the acquired discrimination abilities in agreement with perceptual expertise acquisition. In the first experiment, participants performed the same-different judgments with an equal number of same and different pairs, kanji or checkerboards, across nine daily sessions. We evaluated the effect of practice on performance and the specificity of learning for the stimuli category. In the second experiment, we manipulated the proportions of same and different pairs to induce a response bias (Leite & Ratcliff, 2011; Mulder, Wagenmakers, Ratcliff, Boekel, & Forstmann, 2012) and test if this manipulation reduced or eliminated the bias in the response observed in the first experiment. Two different groups of participants learned to discriminate unequal and inverse proportions of same and different checkerboard pairs of which they had no prior information, across five daily sessions. In the present work, we were interested in the processes of unsupervised experience-dependent visual discrimination learning. Thus, participants performed the task without either trial- or block-based feedback on performance.

2. General methods

2.1. Participants

Adults with normal or corrected to normal vision were recruited through advertisements placed around the Medical School at the University of Chile and received a monetary compensation (approximately 40 US$ dollars). Experiments were conducted in accordance with Protocol #031-2008 approved by the Ethical Committee of the Medical School in the University of Chile in agreement with the Code of Ethics of the World Medical Association (Declaration of Helsinki). All participants gave written informed consent.

2.2. Stimuli

Two types of black and white stimuli, kanji characters (45 exemplars, 17 and 18 strokes), and scrambled checkerboard-like patterns (45 exemplars, 10×10 squares) were selected. Both stimuli were previously used in visual studies (Chen et al., 2013; Civile et al., 2014). Participants had no prior experience with either stimuli as specified in the recruiting interview. Checkerboards were designed with similar average luminance to kanji stimuli, calculated as the mean number of white pixels in the image. Stimuli (1×1 visual degrees) were presented over a black background at the center of the screen, at a distance of 57 cm from the eyes in a CTR 19 in. monitor (Samsung SyncMaster 1100P Plus, refresh rate of 120 Hz), with the software Experiment Builder (v1.6.121, SR Research Ltd., Mississauga, Canada) or in a LCD 20.1 in. monitor (Dell E207WFPc, refresh rate 60 Hz), with NI Labwindows CVI (Austin, Texas, USA).