

The specificity of learned associations in visuomotor and perceptual processing

L. Desanghere · J. J. Marotta

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Abstract Learned associations between object properties, such as weight and size, allow for quick and accurate manipulations of objects that we encounter repeatedly. This integration of learned sensory information reduces the overall computational load of our visuomotor system when interacting with familiar objects. In the laboratory, even novel associations can be quickly established after only brief training. Haffenden and Goodale in *J Cogn Neurosci* 12:950–964 (2000) found that learned associations between color and size affected grip scaling for manual estimations of size and visually guided grasping. But, how specific are these learned associations? In the current study, lighter-shaded “untrained” target objects were added to Haffenden and Goodale’s color-size association paradigm to determine if the learned associations made by the perception and action systems are equally tolerant to within-category color changes. During perceptual estimations, training was generalized within color categories—manual estimations of size were influenced by both the trained and lighter-shaded untrained colors. In contrast, grasping was not influenced by the untrained colored blocks. These results demonstrate how the perception and action systems differ in their incorporation of learned perceptual information. In contrast to the object specific associations needed for grasping, our perceptual system is more categorical and uses generalized perceptual grouping strategies when relying on learned color information.

Keywords Learned perceptual cues · Visuomotor control · Perceptual estimations · Specificity · Categorization · Sensorimotor

Introduction

We move about and interact with objects in our environment so effortlessly that the complexities of these interactions are rarely noticed. When picking up our favorite coffee mug or pen, it is a simple matter to look where we remember leaving it, reach out, and accurately pick it up. But is it really that simple? When we reach out to pick up familiar objects, the posture of our hand and fingers reflect the orientation, shape, size, and function of the object, as well as what we plan to do with it. Our visuomotor system utilizes well established associations between object properties and movement kinematics for anticipatory control of movement. This anticipatory control allows for quick and accurate manipulations of familiar objects without requiring a complete dependence on “moment-to-moment” sensory feedback control about object properties (Gordon et al. 1993).

Two distinct, but interconnected, cortical visual streams have evolved to process the information needed for visual perception and visually guided action (Goodale and Milner 1992; Milner and Goodale 1995). The ventral stream, which projects from the primary visual cortex (V1) to the temporal lobe (Ungerleider and Mishkin 1982), provides us with visual perception of objects and events in the world as well as codes this information for storage and for use in cognitive processes like imagining, planning, and recognition (Goodale 1998; Milner 1998; Milner and Goodale 1995). In contrast, the dorsal stream, which projects from V1 to the posterior parietal lobe (Ungerleider and Mishkin

L. Desanghere (✉) · J. J. Marotta
Perception and Action Lab, Department of Psychology,
University of Manitoba, P404 Duff Roblin Bldg,
190 Dysart Rd, Winnipeg, MB R3T 2N2, Canada
e-mail: umrhode@cc.umanitoba.ca

J. J. Marotta
e-mail: marotta@cc.umanitoba.ca

1982), deals with moment to moment information about the location of objects and is primarily involved in the visual control of skilled movements directed at those objects (Goodale 1998; Goodale and Milner 1992; Milner and Goodale 1995).

Past research has shown how visual information can differentially affect the ventral (perceptual) and dorsal (action) visual systems. For example, dissociations between perception and action have been demonstrated behaviourally in healthy individuals through the use of visual illusions. These studies have shown that while perceptual judgments of location (Bridgeman et al. 1997) and size (Aglioti et al. 1995; Grave et al. 2005; Haffenden and Goodale 1998) are susceptible to perceptual illusions, actions such as saccades (Bridgeman et al. 1997; Wong and Mack 1981) and reaching and grasping kinematics are not (Kroliczak et al. 2005; Milner and Goodale 2006). This research supports the theory that the representations that guide our actions are different from those that guide our perceptions of the world, although alternative explanations for these dissociations have been offered by other researchers (Carey 2001; Franz et al. 2000, 2003; Pavani et al. 1999).

Despite a clear division of labour between the perception and action systems, visual information from both streams work together in our everyday interactions with the world. Properties such as texture, temperature, compliance, and weight may not be fully known when viewing novel objects, but can be learned through direct experience with those objects, thus influencing various kinematic responses such as movement time and grip force prior to contact (Brenner and Smeets 1996; Dubrowski et al. 2004; Gordon et al. 1991, 1993). Indeed, different motor responses are elicited depending on the sensory information associated with that action. Incorporating learned perceptual information about object properties allows for the initial parameters for hand posture and grip scaling to be quickly selected, thus reducing the need for precise metrical calculations about the goal object, while at the same time increasing the overall efficiency of the visuomotor system (Gordon et al. 1993; Haffenden and Goodale 2000).

Research has shown that learned associations can occur relatively quickly, even with uncommon or experimentally derived associations. For example, associations between color and texture (Fikes et al. 1994), weight (Dubrowski et al. 2004), or size (Haffenden and Goodale 2000) have been shown to influence movement time, grip force and maximum grip aperture (MGA; maximum difference between index finger and thumb), respectively during object manipulation. In addition to influencing movement kinematics, Haffenden and Goodale (2000) also demonstrated that learned associations between color and size influence perceptual processes as well. Using color-size

associations, Haffenden and Goodale (2000) repeatedly presented participants with large yellow and small red blocks. Participants quickly developed learned associations between block color and block size. At a later stage when two medium sized blocks were presented, one of which was matching in color to the large yellow blocks and one matching in color to the small red blocks, they found that grip scaling and size estimations were scaled to the color-size association rather than the actual size of that object. That is, after undergoing color-size training, subjects produced smaller grip apertures and perceptual estimations for the yellow medium block than the red medium block, despite these two blocks not differing in size. Haffenden and Goodale (2000) term this effect a “relative size contrast illusion”. Presumably, because yellow had been associated to the larger sized category, the medium yellow block (which was the smallest object in that color category) was perceived as smaller when compared to the medium sized red block (which was the largest object in that color category).

In everyday life, the associations built up by our visuomotor system occur naturally through interactions with objects that we encounter on a regular basis, such as our toothbrush or favorite coffee mug. Our unconscious reliance on learned associations not only allows for quick and accurate manipulations of objects, but also biases our perceptual responses to those objects as well. These built up associations reduce the need to consistently and habitually calculate the precise properties of every object that we encounter when interacting with them. However, a fundamental question concerning this sensorimotor process remains unanswered: How specific is the integration of learned associations during perceptual and visuomotor tasks?

Adapting a color-size paradigm from Haffenden and Goodale (2000), we established an association between block size and block color. In a later phase we introduced both color matched “trained” probe blocks and lighter-shades of the trained target colors (untrained colored probe blocks) that were equal in size. Based on previous research (Haffenden and Goodale 2000), it was expected that after training differences between the trained colored probe blocks (dark red and dark blue) would emerge in both the estimation and grasping conditions. Specifically, the probe block matched in color to the “large” category (dark red) would elicit smaller estimations of size and smaller MGA’s while grasping when compared to the probe block matched in color to the “small” category (dark blue) which would elicit larger size estimations and grip apertures. For the untrained lighter colors, if the perception and visuomotor systems show good specificity for training on the darker colors, then differences in manual estimations and grip aperture while grasping were not expected to emerge. However, if these two systems generalize learned information to

similar colors, then training on the darker colors could carry over to the lighter shades and manual estimations of size and grip aperture while grasping would show the same color-size association effects as the trained colors.

Methods

Participants

After obtaining informed consent, participants were assigned to either a perceptual “estimation” condition ($N = 24$, 19 females, five males; mean age = 21) or a visuo-motor “grasping” condition ($N = 23$, 18 females, five males; mean age = 22). All participants were screened for color blindness (Dvorine pseudo-isochromatic plates; Dvorine 1953), were shown to be strongly right-handed as determined by a modified version of the Edinburg handedness inventory (Oldfield 1971), and had normal or corrected-to-normal vision. This research was approved by the Human Research Ethics Board at the University of Manitoba.

Materials and procedure

In the estimation condition, participants were instructed to manually estimate the size of the testing stimuli (square wooden blocks modeled after Haffenden and Goodale 2000) by opening their thumb and index finger to match the width of the block while their hand stayed in position on the table. In the grasping condition, participants were instructed to reach out and pick up the target blocks using their index finger and thumb. All participants were instructed to pick up these objects as quickly, but as naturally, as possible.

Manual estimations and reaching and grasping movements and were recorded with an OPTOTRAK Certus 3-D motion tracking system (Manufactured by Northern Digital, Waterloo, Ontario). Movements were recorded via infrared light emitting diodes (IREDS; 200 Hz sampling rate) that were secured on the subject’s index finger (positioned on the left side of the cuticle), thumb (positioned on the right side of the cuticle), and wrist (positioned on the radial portion of the wrist) with small pieces of medical tape. All participants were seated at a black table; their starting position was indicated by a white start button which was positioned 10 cm from the edge of the table. Participants in the estimation condition kept their hand stationary on the start button with their index finger and thumb together and their eyes closed. Participants in the grasping condition started each trial with their index finger and thumb resting on a start button and their eyes closed. The experimenter signaled the beginning of each trial with verbal instructions for the par-

ticipant to open their eyes. At this point they had to either make a size estimation of the block, which was placed with its far edge 40 cm from the start button, or reach out and pick up the block. To reduce the noise in the estimation data, participants first viewed the object and then made a verbal signal to the experimenter when their estimation was complete. At that time a 1.0 s recording was taken of their finger position. In the grasping task, a 2.5 s recording was taken from when the experimenter instructed participants to open their eyes. This time frame allowed for the task to be completed and the reach to grasp parameters to be collected. Although viewing times were not controlled in the estimation condition, time to complete the whole experiment did not differ in either the estimation or grasping conditions (approximately 45 min). After the required task was complete, participants in the grasping condition returned to the starting position with their index finger and thumb on the start button with their eyes closed, while participants in the estimation condition simply closed their index finger and thumb and closed their eyes until the verbal command to start the next trial was given. Each participant underwent three different sets of trials, pre-training, training, and post-training, for a total of 172 trials. The testing stimuli consisted of three different groups of blocks, distractors, probe, and key blocks. These blocks were painted one of five colors (reported in C.I.E xyY color coordinates; color readings obtained with a Cambridge Research Systems OP-200E Photometer): dark red ($x = 0.5688$, $y = 0.3692$, $Y = 31.1$), dark blue ($x = 0.3215$, $y = 0.3546$, $Y = 37.1$), light red ($x = 0.5749$, $y = 0.3634$, $Y = 43.6$), light blue ($x = 0.3526$, $y = 0.3836$, $Y = 64.6$), and yellow ($x = 0.5135$, $y = 0.4476$, $Y = 121$). All blocks were 15 mm in height.

Pre-training: The first set of 45 trials established a baseline measure for grip aperture across colors. Five medium sized *probe* blocks were randomly presented five times each alternated between presentations of ten different *distractor* blocks. The probe blocks, which were 45 mm in width, were colored dark red, dark blue, light red, light blue, and yellow. The distractor blocks consisted of five blocks that were 50 mm in width and five blocks that were 40 mm in width. Each of these distractor groups had a dark red, a dark blue, a light red, a light blue, and a yellow colored block. The purpose of these trials was to ensure that size estimations and grasping of the probe blocks were not influenced by the color of the blocks before training began. It was expected that after color-size training, differences in grip aperture and size estimations for the 45 mm probe blocks would emerge.

Training: The next set of trials established the color-size relationship. Six *key* blocks were randomly presented five times each, for a total of 30 trials. These blocks consisted of three large dark red key blocks (65, 70, and 75 mm in width) and three small dark blue key blocks (15, 20, and

25 mm in width). It should be noted that participants were never instructed to attend to the color of the blocks, so any associations that were made between block size and block color (e.g., red = large) happened without experimenter instruction while carrying out either the grasping or estimation task.

Post-training: For the final set of 95 trials both the key blocks and probe blocks were presented. The key blocks were randomly presented ten times each, and the probe blocks were pseudo-randomly presented five times each. Each probe block followed a dark red key block twice, a dark blue key block twice, and the yellow medium sized probe block once. One of the probe blocks was matched in color to the large set of key blocks (dark red) and one was matched in color to the small set of key blocks (dark blue). Two of the probe blocks were lighter shades of these trained colors (light red and light blue) and one probe block was a random color (yellow) which was used for counterbalancing. These probe blocks were used to measure the effect of using color as a cue to size.

Results

To test the effects of color-size training, comparisons were made between the trained (dark blue–dark red) and untrained (light blue–light red) probe blocks in both the estimation and grasping conditions, respectively. Specifically, for the trained colors, size estimations and MGA for the probe block that had the same color as the large key blocks (dark red) was subtracted from the size estimations and MGA for the probe block matched in color to the small key blocks (dark blue), producing a difference score. Positive difference scores are consistent with the “relative size contrast effect” reported in Haffenden and Goodale (2000). That is, larger grip scaling for the dark blue probe block compared to the dark red probe block. Similarly, to look at how specific this training was on perceived object size and visuomotor control, size estimations and MGA for the light red probe block was subtracted from size estimations and MGA for the light blue probe block, again producing a difference score with positive scores indicating larger grip scaling for the blue block. To ensure that the observed size estimations and MGA within the trained and untrained groups were equivalent pre-training, one-sample t-tests were carried out on the difference scores within the colored block groupings (dark blue–dark red and light blue–light red). Furthermore, paired sample t-tests were used to ensure that any within category differences were not significantly different between the trained and untrained color categories. Finally, to look at the effects of training on the trained and untrained colors, a 2 (condition: pre-training, post-training) \times 2 (color: trained colors, untrained colors)

within subjects repeated measures analysis of variance (ANOVA) was carried out in both the grasping and estimation conditions.

Estimations

Prior to training, no significant differences in size estimations were observed within the trained (dark blue–dark red, $t(23) = -0.52$, $P > 0.05$) and untrained (light blue–light red, $t(23) = 0.52$, $P > 0.05$) color categories or between these categories (trained colors vs. untrained colors, $t(23) = -0.74$, $P > 0.05$). A significant main effect of condition [$F(1,23) = 4.31$, $P < 0.05$], but not color [$F(1,23) = 0.60$, $P > 0.05$] was observed for size estimations from pre- to post-training. Thus, after color-size training, the differences within the trained and untrained colors increased significantly. Training on the dark colors influenced both dark and light colored probe blocks in a similar manner as a condition by color interaction was not observed [$F(1,23) = 0.04$, $P > 0.05$]. That is, training was generalized to include lighter “untrained” shades during estimations of size as participants estimated the blue blocks (dark and light blue) to be significantly larger than the red blocks (dark and light red) post-training (see Fig. 1).

Grasping

As with perceptual estimations, significant differences in MGA were not observed within the trained [$t(22) = 1.43$, $P > 0.05$] and untrained [$t(22) = 0.59$, $P > 0.05$] color categories or between these categories [$t(22) = 0.39$, $P > 0.05$] prior to training. Additionally, no significant main effects of condition [$F(1,22) = 0.21$, $P > 0.05$], color [$F(1,22) = 1.25$,

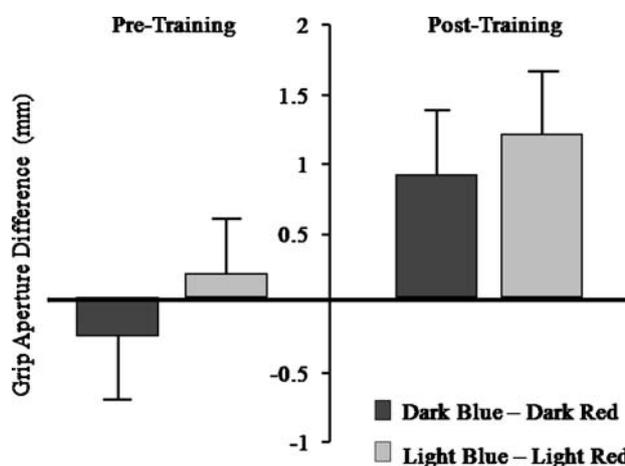


Fig. 1 The pre- and post-training difference scores during size estimations for the trained (dark blue–dark red) and untrained (light blue–light red) probe blocks. Positive differences scores indicate larger size estimations for the blue probe blocks. Error bars depict the standard error of the mean

$P > 0.05$] or any interactions [$F(1,22) = 0.18$, $P > 0.05$] were observed from pre- to post-training. However, despite the Null results revealed by this analysis it is clear that training was having differential effects on the trained and untrained color categories. Indeed, after training the differences in MGA between the trained blocks were shown to increase, while differences in MGA between the untrained blocks were shown to decrease (see Fig. 2). This trend suggests an effect of training for the darker colors that excludes influences on the lighter shades. It is possible that the variance in the data set is contributing to this null effect. When using the same statistical procedures as seen in Haffenden and Goodale (2000), where the strength of the training effect between the blocks are analyzed with respect to differences from 0 (0 being no difference in MGA between the pairs of blocks), one-sample t -tests show a significant effect of training for the trained dark colors [$t(22) = 2.43$, $P < 0.05$] but not the lighter shaded untrained colors [$t(22) = 0.49$, $P > 0.05$]. This would suggest that training on the darker colors was eliciting a larger training effect than seen with the lighter untrained shades. However, as we have seen, these differences do not emerge with more rigorous statistical testing.

According to Haffenden and Goodale (2000), color-size training elicits a directional difference in grip aperture with larger MGA's for the probe block matched in color to the smaller set of key blocks compared to the probe block matched in color to the large set of key blocks (relative size contrast illusion). While this holds true for most participants in this study, it should be noted that an opposite effect of training was also observed: larger grip scaling for the probe block matched in color to the larger sized category. While this opposite direction in training was also noted in

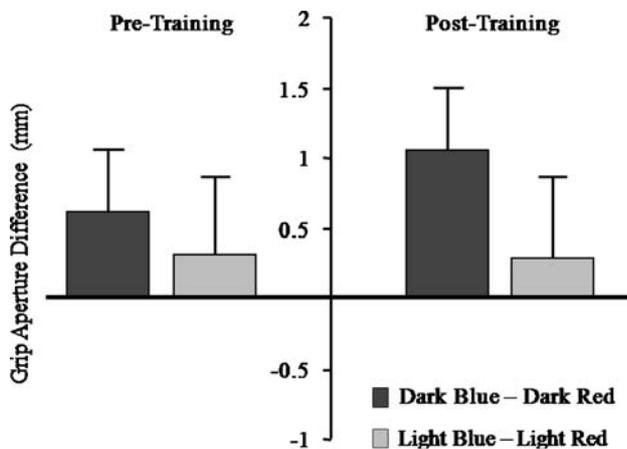


Fig. 2 The pre- and post-training difference scores for grasping. Grip aperture for the trained (*dark blue–dark red*) and untrained (*light blue–light red*) colors were compared, positive differences scores represent larger grip aperture for the blue probe blocks. Error bars depict the standard error of the mean

previous studies (Haffenden and Goodale 2000) and both associations make logical sense, this discrepancy in training direction has contributed to the increased variance observed in this data set as five of our 23 participant showed an opposite association during grasping. It should be noted that seven participants in the estimation condition also made these opposite associations, however the effects of these associations were on average proportionately smaller than those seen in the grasping condition (−1 mm vs. −2 mm).

Discussion

The purpose of this paper was to investigate how specific our perceptual and visuomotor systems are when incorporating learned associations between color and size into perceptual estimations and visually guided grasping. Although the effects of learned associations on perceptual and motor processes have been demonstrated in previous studies, this paper makes a unique contribution to the literature in showing how specific these associations are within the “perception” and “action” systems.

When participants were implicitly trained to associate a specific color to a size category (dark blue = small; dark red = large) and were later presented with medium objects that either matched in color to the learned color-size association or were lighter shades of the trained colors (light blue and light red), perceptual mechanisms mediating size estimations were found to generalize training to “like” colors. Not only were there significant training effects for the trained colors (dark blue–dark red), training also influenced size estimations for the lighter untrained shades (light blue–light red). This type of generalized grouping strategy is consistent with ventral stream processing, which is thought to rely on features that are diagnostic of conceptual categories (Choplin and Medin 1999). This type of processing has been shown to allow for the identification of novel stimuli into members of certain groups or classes which can then be generalized to similar stimuli in the environment (Franklin et al. 2005; Keri 2003) or into different categories of color (Franklin et al. 2005). In the present color-size paradigm this generalized grouping strategy is also observed as both shades of blue were associated to the smaller sized blocks while both shades of red were associated to the larger blocks. As a result, perceptual distinctions between specific shades of colors were not seen. Similar results have been shown during color-picture associations. For example, Zimmer et al. (2002) demonstrated that when a specific color was associated to a picture at encoding, at a later test phase when varying shades of these colors were introduced and participants were required to select the most appropriate color for the picture, within color generalizations were observed. Although participants in the present study did not

have to pick a specific color for the object, color categories, rather than specific color training, were shown to influence size judgments.

In contrast to the pattern seen with perceptual estimations, the same generalizations for color were not observed during visuomotor control. Although significant differences in MGA between the trained and untrained colors were not demonstrated, a larger effect of training on the trained colors was nevertheless shown. When analyzed with the same criteria as outlined in Haffenden and Goodale (2000), increases in grip aperture for the trained color blocks but not the lighter shaded untrained blocks is seen after color-size training. Based on previous literature it is not surprising to see smaller effects on visuomotor control when testing learned associations in a paradigm when perceptual variations are numerous. There seems to be some conditions that must be met for the successful integration of learned cues into visuomotor control. For example, Haffenden and Goodale (2000) demonstrated that when an association between block size and block shape was established, these cues were only integrated into perceptual estimations of size. Grip scaling was not affected by the associations under these circumstances. Presumably because both object shape and object size varied across trials, visuomotor calculations had to be established at each interaction as different blocks required different size calculations and different hand postures. Additionally, using a color size paradigm that varied the location of the object during color-size associations, Haffenden and Goodale (2002) found that the location of the target had to be constant for visuomotor programming to incorporate learned information into grasping. On the other hand, perceived object size was influenced by the learned association regardless of target position.

It seems that when the required movement kinematics are varied during grasping, the incorporation of learned perceptual information into motor programming is prevented. However, our perceptual system is much more versatile in the incorporation of these cues. Results from the present study contribute to this literature by suggesting that after establishing learned associations, if the dependability of the association varies (i.e., presenting lighter shades of the trained colors) the visuomotor system is less susceptible than the perceptual system to exclusively rely on these cues. The present data does, however, show larger effects of training that is specific to the learned associations during reaching and grasping, while no effect of training at all was observed on the untrained colors. This suggests that the visuomotor system is somewhat relying on these learned associations during grip scaling while ignoring the untrained colors. Given that the learned associations were established very quickly in this paradigm (30 trials), longer training times could potentially increase the visuomotor systems reliance on those specific cues and tease out this effect.

Conclusions

The mechanisms mediating our perceptions of the world are quite separate from those guiding our movements within it. Results from this study demonstrate that ventral stream processing relies on a more generalized grouping strategy when integrating learned information into perceptually mediated size estimations; it makes sense that our visuomotor system would not be able to afford such generalizations. When interacting with objects in our environment we need object specific metrical information so that our movements are well formed and accurate. Relying on learned perceptual information to recover stored movement parameters reduces the need for specific metrical calculations each time that we interact with familiar objects. The use of these cues increases the efficiency of visuomotor programming and reduces the computational load of the visuomotor system (Haffenden and Goodale 2000, 2002).

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