**BSF: Investigating the contribution of the motor system to visual shape discrimination**

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**ABSTRACT**

Numerous studies demonstrate a coupling between sensory and motor systems, highlighting the interplay of sensory perception and action as central to successful behavior1–3. Nonetheless, the overwhelming majority of studies in this domain are still unidirectional, showing influence from perception to action, both at the behavioral and neurophysiological level (e.g., social contagion4, mirror neurons5). Less evidence exists of an influence in the converse direction — from motor action to perception, especially so in the visual modality — which is the focus of this proposal.

Findings thus far suggest that active motor engagement may play a significant role in *sensory processing*; they point to differential processing of visual events when they are the product of voluntary movement rather than passive observation. Such *sensory modulation* induced by motor engagement has been measured in both behavioral and neurophysiological responses in both animal and humans6–12. However, the contribution of motor-induced sensory modulation to *sensory* *learning* is largely unknown.

In this project we aim to explore the influence of action on visual learning. Specifically, we aim to explore whether engagement in tracing of shapes facilitates their visual perception and promotes visual discrimination between them, and to elucidate the mechanisms responsible for this potential facilitation.

Expected conclusions will provide an empirical evaluation of approaches commonly employed in education13,14, and suggest avenues for the design of research-driven interventions. Of particular interest to us is the potential contribution to supporting visual recovery of congenitally blind patients after sight-restoring treatment (‘Project Prakash’)15.

**BACKGROUND**

How does the visual system learn to process shape and contour information for the perception of forms?

Adults can perform discrimination and identification of different visual patterns with apparently little effort. This ability involves a complex set of perceptual and cognitive abilities that develop over time. For example, the task of matching differently shaped blocks to corresponding holes is trivially easy for a typical adult but challenging to a toddler16. The fact that perception of complex shapes is tightly linked to developmental age level, continuing until early adolescence17 attests to the protracted procedure of learning to process shape information. Even in adulthood, learning to discriminate between novel complex shapes requires time and practice, and the underlying mechanisms are not fully understood.

The position we adopt here is that active motoric engagement may contribute to the task of visual shape learning. Specifically, we aim to explore whether engagement in tracing of shapes promotes their visual discrimination. We will do so by examining the independent and additive contribution of different aspects of motor engagement and the corresponding visual information on learning to visually discriminate between shapes.

Our position is based on past evidence points to motor-induced modulations of perception. It has been shown that active self-triggering of a visual stimulus modulates its perception (e.g., perceived intensity11 and speed8), and relatedly, the evoked neurophysiological responses to it9,10, relative to identical stimuli triggered externally. There is evidence that actively triggering a visual stimulus improves performance on tasks related to it, such as detection of dot movement direction18 and the existence of temporal delay19.

Everyday tasks that intuitively couple actions with visual outcomes involve *pattern production* by drawing and writing20–23. Studies examining the influence of handwriting practice on literacy have explored the influence of graphic pattern production through *curve tracing* (following the contour of a template symbol with a superimposed trace) and through the related tasks of *copying* (reproducing a symbol while observing it in a different location in space) and *handwriting* (reproducing a symbol from memory). This body of research has shown that visuo-motor experience with symbol reproduction can lead to enhanced visual recognition, exceeding improvements with other types of motor engagement, such as typing the same symbols24–28. Neuroimaging data collected during symbol production reflects a concurrent recruitment of visual areas (occipitotemporal cortex) together with downstream parietal and motor regions and suggests that visuo-motor experience establishes and strengthens functional pathways between visual and motor systems29.

Several motor and visual aspects of pattern production might support enhanced visual recognition30. One *motor aspect* is the natural coupling of action with highly predictable visual feedback that accompanies it, resulting in continuous motor-visual congruence31–33. It has been hypothesized that the strengthening of functional connections between motor and visual brain regions is facilitated by their temporally linked recruitment during visuo-motor activity29,31. *Another* aspect from the motor perspective of drawing that might affect visual recognition is related to the motor circuit used while drawing the shape. Even though studies examining the influence of action on perception mostly look at motor influence as either present or absent, recent evidence suggests that the manner (‘how’ the action was performed) also matters. It was previously found that the identity of the active hand (right/left) modulates perception and neural representations of the action outcome in a different manner6,34. Thus, sensory regions contain information, not only about the physical properties of the sensory stimulus, but also about the motor commands that were used to generate it. Given these results, it is plausible that the identity of the active hand will also affect learning and neural representations of different visual shapes.

A *visual* *aspect* of drawing that might enhance visual recognition relates to the nature of the visual feedback emanating from the pen, which results in dynamic temporal evolution of the traced shape. This dynamic visual information may contribute to visual shape recognition independently of the visuo-motor contingency - an idea which is supported by evidence that dynamic information facilitates shape and object perception35,36. A possible mechanism for such visual contribution may be through engagement of the motor system, as has been demonstrated during action observation37,38. Previous studies have shown that observing a dynamic replay of handwriting activates motor related regions even in the absence of active movement39–42. Nevertheless, it is still an open question whether observation of dynamic shape information can enhance the ability to extract shape information. Moreover, even though the motor and visual aspects of tracing are tightly linked, the relative influence of each on visual shape processing is still not known

**OBJECTIVES**

The goal of our project is to further the understanding of the involvement of motor-visual interaction in visual learning. To this end, we will attempt to elucidate the influence of different components of visuo-motor engagement on the process of learning to discriminate between different visual shapes.

We will explore whether and what aspects of training on a *shape tracing visuo-motor task* yields improvement in *visual shape discrimination*. To assess the different components of the action-to-vision influence, we will disentangle motor and visual aspects of visuo-motor performance. Specifically, we will explore the interplay of motor *production* and *laterality* of motor circuit (hand identity) with the visual component’s characteristics(*temporal dynamics* and *spatial variability*).

**RESEARCH DESIGN AND METHODS**

To explore motoric influence on visual learning and identify factors involved in this process, we propose a behavioral training paradigm, in which the components of visuo-motor engagement in the task of shape tracing are disentangled by experimental manipulation of the motor and visual factors composing it. This paradigm will allow us to explore the factors of motor engagement that support visual learning and facilitate longitudinal improvement of visual shape discrimination performance.

Our study will address the following questions:

1. Given that *perception* is modulated by motor engagement: Is *learning* of visual shape discrimination facilitated by experience with shape production?
2. Given that sensory regions are sensitive to the laterality of the stimulus-generating hand: Do different motor circuits affect the level of improvement in visual shape discrimination? Specifically, does engagement of the left or right hand change the level of shape discrimination performance?
3. What visuomotor aspect of tracing facilitates visual shape discrimination? Specifically, does mere observation of the temporal evolution and spatial variability of the shape contours facilitate visual shape discrimination independently of motor engagement?

Our experimental approach to the investigation of these questions will include using psychophysics to assess observers’ visual discrimination accuracy between novel shapes and measuring the improvement in this skill (reflecting learning) after different types of training.

To allude to the mechanism of visual shape learning and to tease apart the relative contribution of motor factors (*motor engagement*, identity of *producing hand*)and visual factors (*temporal dynamics* and *spatial variability* of produced traces) to the process, we will investigate the specificity of improvements to different training conditions, as specified below.

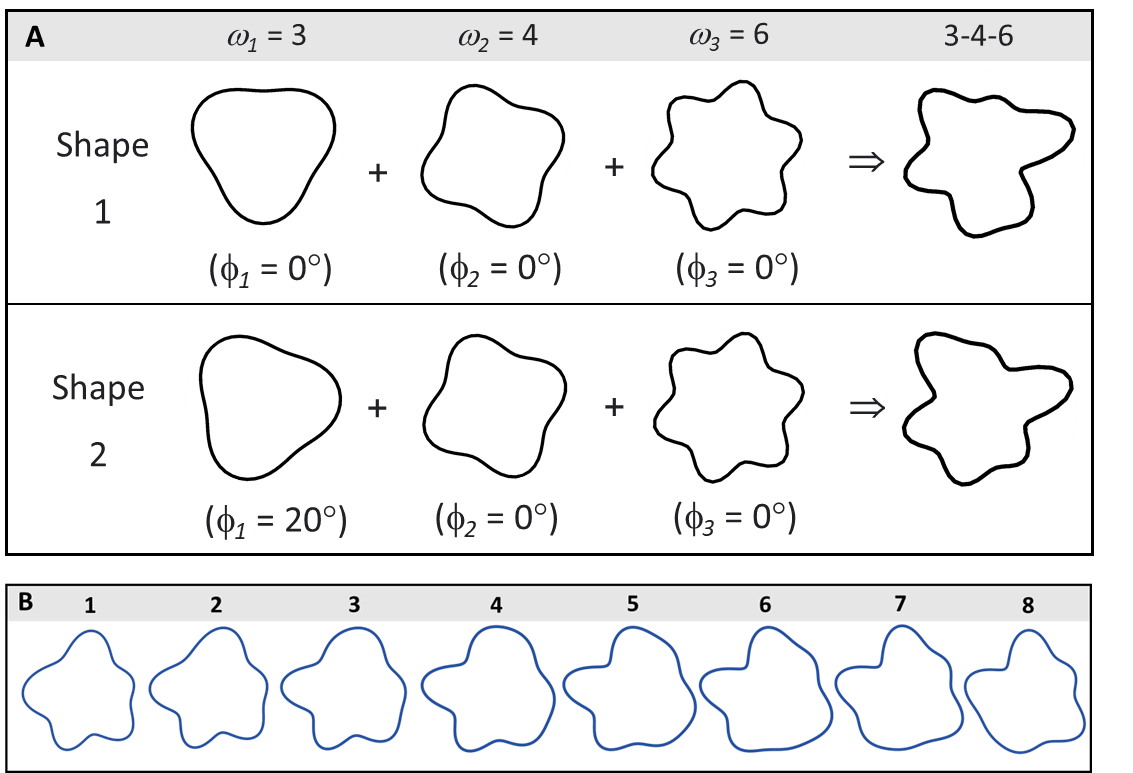
**Participants:** 130 healthy, right-handed normally sighted adults (age 18-35) in total will participate in the experiment (20 per condition X 6 conditions = 120 + 10 pilot participants). Hand dominance will be determined by self reports and the Edinburgh handedness test43.

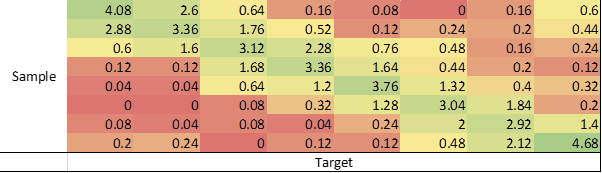
**Stimuli synthesis and validation:** Stimuli consist of 2D amoeboid shapes (closed contours with protrusions and intrusions (‘bumps and dimples’), synthesized based on mathematical characterization of compound radial frequency (RF)44. Basic RF patterns are created by modulating the radius of a circle by a sinusoidal function of the polar angle, and compound patterns are created by combining several basic patterns (Fig. 1A), in a manner akin to Fourier synthesis45. These types of shapes have previously been used to study intermediate-level shape processing in human observers46,47. Such shapes have been argued to be ecologically appropriate since they are easily modified to create natural shapes (e.g., faces, animal heads, torsos, and fruit)48.

For the purposes of our experimental design, shapes needed to be constructed as highly similar, so that visual discrimination between them would be difficult enough to leave latitude for improvement on a shape discrimination task. Additionally, the perceptual difference between shapes needed to parametrically progress across the stimuli set with equal steps, so that each shape is as equally easy to discriminate from the shape most similar to it.

To fulfill these requirements, we used the RF compound shapes’ mathematical characterization to synthesize them such that they are parametrically adjusted for stepwise control over their visual similarity. Specifically, we synthesized eight shapes (Fig. 1B), all derived from the same combination of basic RF patterns, thus being highly similar to one another, with the only difference between the different shapes being that one of the composing RF patterns is oriented differently for each member (Fig. 1A). Finally, we equated the perimeters of all shapes so that all target tracing paths are rendered to be of equal length.

We empirically validated that this stimuli synthesis procedure resulted in stepwise perceptual similarity by testing human visual discrimination between these shapes. To this end, we used the same procedure to be implemented as a visual assessment for tracking visual shape learning before and after training (see Fig. 3A for an illustration of the validation task). Our testing of 25 subjects demonstrated (Fig. 2) that the target shapes were confused with shapes similar to them. These procedures for constructing and validating stimuli have been completed and we now have validated stimuli (see Fig. 1B), which we have used in pilot experiments of this study (see below).

***Fig. 1. Stimuli.*** *Illustration of the construction of two complex RF pattern shapes.* *Both shapes are composed from the same basic RF patterns, when only the phase of the first basic pattern (ω1) differs between them.* This fulfils the requirement of parametrizing equal steps between shapes. *B. The stimuli set constructed using this methodology.* 

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***Fig. 2. Validation of parametric stimuli perception.*** *We empirically validated that this procedure resulted in stepwise perceptual similarity (i.e., that each shape is as equally easy to discriminate from the shapes most similar to it) by testing human visual discrimination performance of 25 participants. Each participant could choose each sample shape (across eight repetitions) between 0 to 8 times. The legend shows the color coding from low (red) to high (green) numbers. The oblique measures the average number (across subjects) of correctly selecting the target shape from the sample set. On average, the hit rate was near 50% (3.54 of 8). Errors were concentrated along the oblique of the matrix, reflecting confusions of the target shapes with shapes similar to them.*

**Experimental Procedure:** All experimental conditions will be run on an upward-facing 21.5’’ Wacom DTU-2231 digitizing tablet. At the beginning of the experiment, we will inform participants that our aim is to explore improvements of their visual discrimination ability as a result of the training they will undergo. The experiment will consist of two types of tasks - a visual assessment task and a training task.

**Visual assessment task:** To assess our participants’ ability to discriminate between shapes, we will use a delayed match to sample design (Fig. 2A). Each trial will be initiated by the participant placing the stylus at a designated location at the bottom center of the screen (marked as the home location), to indicate their readiness. A trial will begin with the target shape presented for 1000ms, followed by a 300ms visual mask, and a screen with all the shapes in the sample set, presented on a semi-circle, equidistant from the home location. Participants will be instructed to indicate which among the sample set is the target shape (shown in the first screen), by reaching to the chosen shape as quickly as possible. Each shape will serve as target 8 times (yielding 8x8=64 trials per family), and presentation location of the samples will be counterbalanced across trials.

**Training task:**Each participant will be randomly assigned to one of six training task groups which include two visuo-motor training regimen groups (right / left hand tracing), and four visual training regimen groups (dynamic / static visual input, from right/left hand traces).

*Visuo-motor training* will include tracing of shapes and receiving visual feedback of the trace as it is formed. Participants assigned to one of the visuo-motor training regimens will be asked to use an electronic stylus to trace a template of a different shape in each trial. Shapes from the training set will be randomly ordered across training. Shapes will be traced continuously for one full cycle, in a comfortable natural pace. Participants will see the reference template throughout the trial, and their trace will form in real-time overlaid on the template, as if drawing with a pen on paper. Any starting position and direction of tracing can be freely chosen by the participant. Prior to the training session on the first day, each shape will also be traced one time in a pre-training run, so participants are comfortable with the set-up and familiar with the shapes before training begins. Tracing will be performed either using the *non-dominant left hand* or the *dominant right hand,* according to the assigned training group (Fig 3B upper panel)*.*

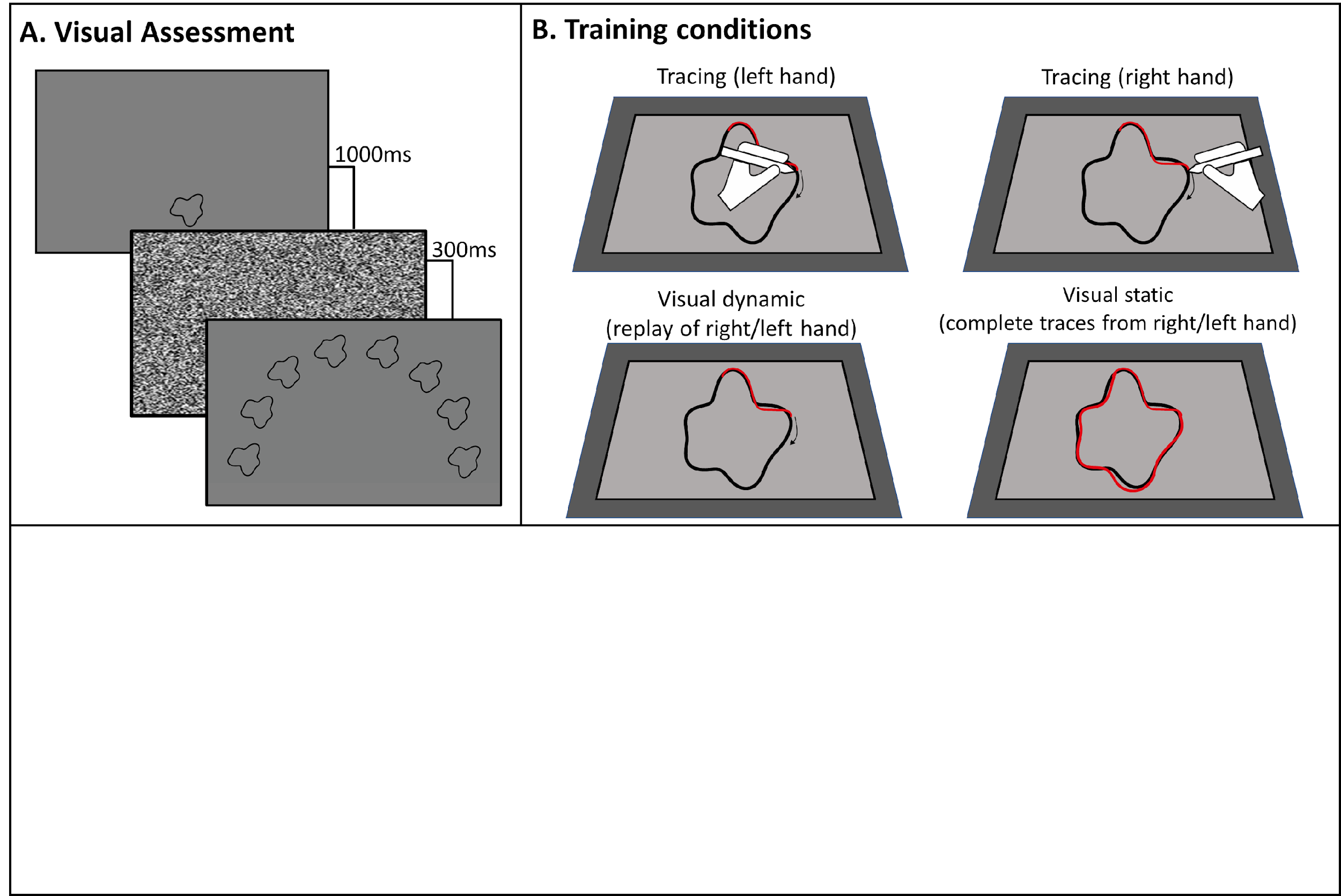
*Visual training* will include observation of natural shape traces that were recorded during production by other participants in the visuo-motor training groups. Each pair of participants assigned to the visual group will be randomly yoked to one reference participant in the visuo-motor group. Participants will observe the visual output of their reference participant’s tracing overlaid on the corresponding template that was traced, in the same order as it was performed. One of these participants will be assigned to the*dynamic visual input* training group and observe videos of the reference participant’s produced traces evolve over time, and the other participant will be assigned to the *static visual input* training group and observe a static image of the full end-point trace, appearing at once and presented for the duration it took to be traced (Fig 3B lower panel).

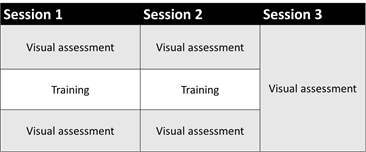
For all training regimens, shapes will be presented in the center of the screen and take up 14 degrees of visual angle. Each shape will be repeatedly traced or observed 25 times throughout each training session, for an overall of 200 trials per training session (8 shapes x 25 repetitions). Based on our pilot experiments, this takes approximately 50 minutes to complete in the first session, and duration decreases as participants become more skilled and increase their movement speed. Our pilot results (Fig. 3) indicate that this amount of training corresponds to concurrent improvement in visual perception. Further exploration is needed to ascertain the different training conditions that are most efficient in inducing this improvement.

The complete experiment will include 3 sessions overall, within an 8-day period: 2 sessions on consecutive days for the training regimen, and another post-training assessment session (1 week after the first training session) to measure retention of visual shape discrimination. Each of the two training sessions will start and end with an *assessment* *of visual discrimination* between thetrained shapes, before and after the *training task*. The third, post-training session will include only a visual assessment.

**Maintaining and monitoring participants’ attention throughout the training session.** An additional sixteen *catch trials* (2 per each shape) will be intermixed with training trials (randomly ordered) in each of the training runs. The catch task is to detect a transient increase in width of a segment of the template, persisting for 1200ms. Our goal with this catch task is to engage the participants and motivate them to observe the template shapes, as well as the trace, in the area surrounding the pen tip. The change in thickness will occur in one of four equal length sectors of the top half of the template shape (sector randomly assigned in each run and counterbalanced across runs) and appear mid-through tracing of the template in the corresponding sector. The reason for not presenting catch trials in the bottom half of the shape template is that in this area, as we discovered through pilot testing, the hand may partially obstruct the template in some regions and result in missed catch trials.

At the end of each training session, participants will be given feedback on their performance on catch trials (percent of correct answers). We will use this percentage to monitor the engagement of the participants and to exclude participants that respond below a predetermined threshold. More crucially, since participants cannot predict when catch trials appear they will need to maintain attention to the tracing and the template portion being traced to not miss them. The same catch task will be performed in all training types (visuo-motor, dynamic and static visual training), to minimize differences in attention between all training groups.

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*C.*

***Fig 3. Experimental tasks.******A.*** *Visual assessment design - delayed match to sample. Participants will be presented with a target shape for 1000ms, followed by a visual mask, and an array of all the 8 shapes in the training set from which they will need to indicate which was the target.* ***B.*** *Training conditions scheme. The visuo-motor condition (upper panel) will consist of active tracing of the entire shape using either the right or left hand. The visual dynamic condition (left lower panel) will consist of a replay of the same traces from the visuo-motor condition. The visual static condition (right lower panel) will consist of observing the complete trace for the same amount of time it took to trace it.* ***C.*** *Experiment flow.*

**Visual discrimination learning measure:** For each assessment task, we will define performance as the percent of correct responses (hits) in the template matching task. Visual discrimination learning will be assessed as improvement following training, quantified as the difference in performance between assessment tasks, within/across days. *Longitudinal learning* will be measured across the (two) training sessions and *retention* will be assessed by measuring performance in the (third) retention session.

**Tracing evaluation:** To measure differences in the quality of visuo-motor tracing, which serves as the output of the visuo-motor training conditions and the input of the visual conditions, we will assess:

(1) The *variability* of repeated tracings of each participant over time, which reflects their ability to perform tracing in a consistent manner.

(2) The *accuracy* of the participants' tracings (e.g., compared to the reference shapes), which reflects their ability to coordinate hand movement in congruence with the visual shape template62–64.

(3) The characteristics of the dynamical evolution of tracing by applying measures of movement kinematics which reflect *motor skill* and acquisition of a motor sequence planning strategy.

These tracing measures and their evolution across time will be compared between participants trained with right versus left hand training conditions. We will also use these analyses to correlate (across participants) between motor skill and visual learning (see below, analysis 3).

Specifically, to assess (1) *shape variability*, we will tailor the analyses to the specifics of our dataset. This, since meaningful quantitative measures and comparisons of 'shape' are notoriously difficult to obtain, especially when these metrics are assumed to be perceptually relevant, so as to be used psychophysically49–51. Therefore, our approach relies on an ensemble of measures, many defined in scale-space, which allow for analysis and comparison of global and local spatiotemporal features of the stimuli and responses. First-order measures (such as aspect ratio, area, path length, etc.) can be further combined to produce higher-order metrics such as complexity and compactness. Differentiation of these first-order measures then yield the differential geometry (gradients, curvatures, and such, as well as even higher order integration and differentiation of them) that can be further considered at a range of global-to-local scales (e.g., a scale-space).

To assess (2) *tracing accuracy* (differences between reference template shapes and participant tracings), we will use difference and distance measures, such as the Wasserstein (aka earth mover’s), area between tracing and the corresponding reference pattern, and Pompeiu–Hausdorff distances52.

To assess (3) *motor skill* improvement, defined as greater co-articulation among consecutive motion segments28 resulting in greater length of motion segments67, we will perform kinematic analysis of tracing movement. When production of specific patterns is well-trained, it begins being controlled through global motion planning29, as reflected by a reduction in online corrections of the path and in smoother and less segmented movement. Learning therefore requires some level of representation of the shape of the path, which may in turn aid visual shape processing and learning. We will examine whether the development over practice of smooth concatenation of the movement elements used to assemble the shape53,54 co-varies with visual learning of the shape.

**Analysis 1**: To answer questions 1&3 regarding the influence of shape production on visual shape discrimination, we will compare visual discrimination improvement following visuo-motor vs. dynamic visual training. Similarly, to address question 3 regarding the role of dynamic visual input on visual shape discrimination, we will compare visual discrimination improvement following dynamic vs. static visual training. These will be performed with a one-way ANOVA on the visual discrimination performance measures, collapsed across hands, with training condition as an independent factor. Greater discrimination improvement in one of the training conditions will imply a facilitating effect on visual discrimination, while similar levels of discrimination improvement would imply that visual discrimination improvement is invariant to the training regimen.

**Analysis 2:** To answer question 2, regarding the influence of different motor circuits producing the trace on facilitation of visual shape discrimination, we will compare visual learning levels following right-hand vs. left-hand training. A difference in learning between these conditions will indicate different involvement of different motor circuits in learning, while similar levels of learning in the two visuo-motor conditions would imply that visual learning is invariant to the differences between motor circuits controlling the different hands.

In case we do find a difference in visual learning between hands, a potential alternative explanation to differences in motor circuits could be differences in visual feedback such as the (expected) larger variability in trace output of the left (non-dominant) hand. In such a case, a similar comparison of visual learning across hands will be performed in the dynamic visual condition. If we do not find similar learning differences across hand output in the visual dynamic modality, we would conclude that variability in the visual output is not the source of difference we find in the visuo-motor condition. This would point to specific, hand-dependent motor circuits that facilitate visual learning. Alternatively, if similar hand differences are also found in the dynamic visual condition, we would conclude that hand differences in the visuo-motor condition are not specific to engagement of different motor circuits and that hand differences we find may be better explained by variability in the visual properties of the traces produced by the dominant vs. non-dominant hand.

The source for this difference could stem from variability of the dynamical evolution and / or by variability in the visual characteristic of traces produced by the skilled versus unskilled hand. This distinction will be partially addressed by comparing hand differences between dynamic and static visual training, thus alluding to the importance of kinematic information; if we find hand difference when learning from dynamic traces, but not from static images of the trace, we will conclude that differences in dynamical evolution are likely among the drivers of this perceptual learning difference, but if the hand difference is similar between dynamic and static training, this will suggest that the visual characteristics of the trace play a bigger role in the difference between learning from the right- versus left-hand traces.

**Analysis 3:** To explore the possible mediating factors of visual shape discrimination learning, we will test for correlations (across individual participants) between visual learning (measured as improvements in the visual assessment) and quantitative measures of characteristics of the produced or observed traces (depending on the training condition), to explore if any of these measures co-vary with the level of learning. A significant correlation between visual learning and evolution of shape consistency (tracing evaluation 1, above) or tracing accuracy (evaluation 2) would suggest an effect of these visuo-motor components on visual learning. A significant correlation between visual learning and measures of motor skill improvement (suggesting motor planning strategy acquisition, evaluation 3) would support the notion of motor-induced visual learning.

**Preliminary results:** We have collected pilot data which attest to: (1) the feasibility of running the experiment and (2) the potential effect of visuo-motor training on visual shape learning. We first collected nine participants performing the visuo-motor task over 2 training sessions (VM\_RH, Visuo-Motor tracing of the shapes with their Right dominant Hand). This group of participants (Fig. 4, left panel, blue circles) showed a mean improvement of 18.05% which was significantly different (p=0.0004) than 0% improvement. In order to assess the relevance of training to this visual learning effect and to confirm that these improvements in visual discrimination were not solely associated with experience due to repeated exposure to stimuli during repeated visual assessment, we ran a control group of six participants, who were assessed for visual discrimination between the same set of stimuli shapes (Fig. 1B) but trained on a different set of shapes from those included in the visual assessment. (NT\_RH, No relevant Training, Right Hand). This group of participants (Fig. 4, right panel, yellow triangles) also learned, though to a lesser extent than the group with relevant visuo-motor training. They showed a mean improvement of 10.16% which was significantly different (p=0.0165) than 0% improvement. Performance on catch trials was high and similar for all participants in both conditions across both sessions (VM: 98.0%, NT: 96.75%).

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***Fig. 4. Preliminary data.*** *Longitudinal learning in the visuo-motor right-hand training condition.**Plots show improvement of visual assessment performance (computed as the difference between hit rate after training on the second day and hit rate before training on the first day). Each marker is one participant. The left panel (blue circles) shows improvement in visual discrimination between shapes after engaging in their right-hand tracing. The right panel (yellow triangles) shows improvement after engaging in right-hand tracing of a different set of shapes not used in the assessment.* ***The results suggest that***

Descriptively, training with relevant shapes seems to have had a greater effect, as four of the participants with relevant visuo-motor training had larger improvements in discrimination performance compared to participants who underwent visuo-motor training on an irrelevant set of shapes. This suggests that visuo-motor engagement with tracing of a shape is an important driver in learning to discriminate it. Completion of our planned paradigm will reveal if it is necessary to be engaged in motor production to achieve such learning, or the same /similar performance can be achieved through visual observation. A complete dataset will also allow us to explore potential drivers to the variability of visual learning between different participants (Fig.4, left panel), by testing for co-variance between visual learning and trace characteristics (see analysis 3).

Note that although this control condition was run as a “sanity check” preliminary step, this type of control will not be necessary with the results of the full paradigm, as the outcome measures will be a comparison of visual discrimination improvement between groups. Since all groups will undergo the same visual assessment procedure, this effect will be canceled out by the comparison, which should reveal only improvements which are above those induced by repeated exposure during visual assessment.

**SIGNIFICANCE**

*Scientific value:* Our project addresses the notable gap between a large literature on influence from visual perception to action (and evoked neural activity in motor regions), and a sparse literature on influence in the converse direction, from motor action to visual perception.

This literature is especially sparse in the context of learning. While motor learning from perception is well-established (learning by observation)38,55,56, learning processes in the converse direction (motor-induced visual learning) have scarcely been explored (but see57,58).

This collaboration will make significant contributions to the understanding of visual-motor interplay by helping to identify factors involved in motoric facilitation of visual processing. A better understanding of the factors that facilitate visual discrimination between shapes, a task which involves a complex set of perceptual and cognitive processes, will enhance our knowledge about the mechanisms for integration of perception, action, and cognition. Our results will contribute to future attempts to construct a comprehensive model that can incorporate motor action in visual shape processing and learning.

*Practical implications:* Understanding the mechanisms of sensory-motor interactions for facilitating visual shape discrimination is relevant to the design of routines for inducing perceptual learning. In educational settings, tracing of geometric shapes as a teaching method is common practice13,59, but not sufficiently based on an empirical exploration of its effectiveness for visual shape learning14. Our project will provide empirical evaluation of this practice. Moreover, our in-depth assessment of the relative contribution of different factors to visual shape learning may open avenues to approaches for helping students integrate shape information, for example by utilizing laterality effects through engagement of the non-dominant hand, or through kinematic observation. These effects uncovered by our investigation may impact the design of motor-sensory interactive educational tools for shape learning60,61.

Of particular interest to us is the field of rehabilitation, particularly of patients with atypical visual development. The Sinha group has had the opportunity to conduct a unique program in India in which surgical intervention is provided for children with treatable congenital blindness, and their perception is studied as they learn to make sense of the world when they begin to see after cataract-removal surgery late in life (Project Prakash15). Despite the effective reversal of their blindness, these children, and many like them worldwide, exhibit difficulty in naturally learning to recognize visual shapes, as revealed by ours (Fig. 5) and others experiments62. Effective methods for improving these skills63,64 are of profound importance for such children, as these challenges compromise their ability to take-up reading of print, basic geometry and even object recognition. We hypothesize that the development of these patients’ visual shape recognition ability can be promoted by engagement in visuo-motor behavior with precise control of the factors that will be proven as facilitatory from the currently proposed project.

Graphical user interface, application

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***Fig. 5. Visual shape learning following visual restoration.*** *Shape discrimination (tested by a delayed match to sample task) can naturally improve with time after surgical treatment from removal of congenital cataracts, but ceiling performance is not reached on this easy task even 1-2 months after surgery (n=4 patients, SE across participants, chance level is 1/6).*

The results obtained in the current project will guide our plans to address specific rehabilitation needs of these children after their surgical sight restoring treatment. In this vein, we are in the process of providing seventy of the newly sighted children with digital tablets. Although studies with Prakash children are beyond the scope of this proposal, we do want to provide a brief overview of how results from this work will be translated towards the design of training routines for Prakash children; Applications that we intend to upload to the tablets will involve requiring the children to trace letters of the English and Hindi alphabets and to trace simple drawings and shapes. We expect that these activities will facilitate letter and shape learning by the children, and thereby help with their educational and rehabilitative progress. To assess this, we will include another application requiring the children to discriminate between shapes before and after they engage in tracing, similar to the visual assessment in the current project (Fig. 3A) and to experiments previously run with Prakash children (Fig. 5). In parallel, Project Prakash has initiated a school program, in which longitudinal assessments of visual shape recognition are combined with schooling and with periodic assessments in related fields (literacy, geometry, spatial cognition), serving as a platform for testing the broad effects of rehabilitation efforts on educational aspects.

*Sharing of stimuli synthesis method and data:* Our novel approach to stimuli synthesis, of constructing shapes (Fig. 1A) with parametric differences that are validated against human perception of visual differences (Fig. 2) will be useful in other research settings, whenever explicit, and parametric, control over the visual similarity of shapes is required.

The comprehensive database built through our experiments, which includes shape tracings collected from different individuals across multiple sessions with corresponding visual discrimination performance between the shapes, will also be made publicly available. This database will provide the largest set we know that consists of multiple dynamic segments of shape tracing during a training process. We believe that it will serve as a resource for researchers with interests such as sensorimotor development, brain plasticity, rehabilitation, and education in STEM fields, to test hypotheses regarding associations between motor skill development and visual shape learning. It can also serve as a basis for computational modeling of these processes.

**Collaboration Between the sites:** Furthering the understanding of motor-visual interactions for shape processing requires expertise in the (historically independent) research domains of motor control, visual processing, and shape perception. Our interdisciplinary collaboration accomplishes this complex requirement. The proposed studies build on the unique and complementary expertise of the collaborating principal investigators. The project will involve joint planning of research, to be physically conducted in TAU. The analysis will be divided between the three sites according to the field of expertise (see timeline, below, for specifics), and evaluation of results will be joint.

**Prof. Mukamel’s (TAU)** expertise is in the study of the neural basis of action and perception, using motor training and motion tracking paradigms65. Some of the findings supporting the notion that sensory modulations are rooted in motor origins, a notion which has formed the foundations for the proposed project, come from his previous studies34,66.

**Prof. Sinha (MIT)** is an expert in the study of vision development mechanisms using behavioral, electrophysiological, and computational approaches. In preparation for the current project, his group (in collaboration with Dr. Ben-Ami, below) has examined the effects of different types of visual feedback for improving visuo-motor skill of the left non-dominant hand67.

**Prof. Phillips’ (RIT)** expertise is in employing mathematical characterization to construction of natural shapes for vision and haptic experiments and in the psychophysical study of ecological perception. In some of his previous work he has established that motion information enhances the extraction of visual 3-D object shape36. We will use similar comparisons of static and dynamic conditions to explore and quantify the enhancements in *learning*which can be attributed to the addition of dynamic information. Phillips and Sinha68 have previously tested how the nature of exploration influences the ability to extract shape information in the tactile modality. In the current project we will apply a similar approach to the visual modality, by testing the ability to extract shape information from different types of visual information intake (e.g., active production of visual shape traces versus passive observation of dynamic shape traces).

**Dr. Ben-Ami**, **MD** **(TAU, Project Prakash)** is a medical doctor with clinical background in neural rehabilitation, and scientific background in the fields of visual perception and motor control, with experience in psychophysics, mathematical modeling, motion-tracking, and kinematic analysis. She has extensive clinical experience applying interventions for inducing plasticity and learning in cases of atypical sensory-motor processing. She is beginning her second year as a TAU Minducate Center research associate in the Mukamel Lab. Previously she was a part of the Sinha Lab for 4 years, where she performed research on the Autism project and the Prakash Project, and prior to that a post-doc in the Flash motor control lab in the Weizmann institute, studying the sensorimotor aspects of Autism.

**Batel Buaron, M.Sc. (TAU Ph.D. student, Mukamel lab)** has conducted and published several behavioral and fMRI papers under Prof. Mukamel’s supervision during her M.Sc. studies, including studies which have formed the foundations for the proposed project6,69. She will be involved in all aspects of the proposed research taking place at TAU and will contribute to the formulation of scientific manuscripts and presentations in vision/neuroscience/motor-control conferences.

**Facilities, resources, and equipment (TAU):** The Mukamel Laboratory has exclusive use of two dedicated behavioral testing rooms and two offices for faculty, student and postdoctoral staff, all on the same floor. Laboratory rooms are fully equipped for performing the proposed project. The lab employs a half-time lab manager who provides logistic support in order to ensure all systems and equipment operate smoothly with minimal disruptions to ongoing research activities.

**Feasibility, Challenges & Solutions:** The main barrier to a multi-day experiment such as suggested here is high drop-out rates, which we will reduce by offering bonus pay for study completion. Prof. Mukamel and Prof. Sinha have both run studies involving training across several days65,71. The Mukamel Lab has recently completed a behavioral training study with procedures similar to the ones planned in the current project (140 participants tested on two consecutive days), reflecting the logistic feasibility of conducting a study of such large magnitude in TAU, even while complaining to the restrictions of the global pandemic.

A potential challenge with multi-lab projects is the coordination between sites. We will address this by conducting bi-weekly group meetings over video conference (more whenever necessary), and in person meetings once a year, to facilitate experiment set-up and collaborative result evaluation and manuscript preparation. Members of the research group have collaborated in the past: Professors Sinha and Phillips have collaborated on many projects and their complementary contributions have proven fruitful68,70, while Dr. Ben-Ami (now a member of Prof. Mukamel’s lab) served as a postdoc on Prof. Sinha’s projects for four years, one of which was in collaboration with Prof. Phillips. Dr. Ben-Ami’s extensive familiarity with all the collaborators, in combination with her research experience in the fields of motor control and human visual perception, puts her in an ideal position to successfully steer the proposed collaboration.

**Timeline.**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | **Completed** | **Year 1** | **Year 2** | **Year 3** |
| **M**  **I**  **T** | Assessing the effect of visual feedback (trace versus no-trace) for improving visuo-motor skill. | Develop kinematic analysis.. | Apply kinematic analysis. | Complete data collection and analysis.  Presentation in conferences.  Manuscript preparation.  Preparations of joint clinical grant submissions based on our findings. |
| **R**  **I**  **T** | Stimuli construction and validation. | Develop and apply shape variability analysis. | Apply shape variability analysis. |
| **T**  **A**  **U** | Set-up & initial piloting  of experiments. | Data collection and analysis of visual discrimination performance. | |

Abstract in lay terms:

**BSF: Investigating the contribution of the motor system to visual shape discrimination**

How does the visual system learn to recognize patterns?

Adults can perform discrimination and identification of different visual patterns with apparently little effort. This ability involves a complex set of perceptual and cognitive abilities that develop over time. For example, the task of matching differently shaped blocks to corresponding holes is trivially easy for a typical adult but challenging to a toddler. The fact that perception of complex shapes is tightly linked to developmental age level, continuing until early adolescence, attests to the protracted process of learning to process shape information. Even in adulthood, learning to discriminate between novel complex shapes requires time and practice, and the underlying mechanisms are not fully understood.

The position we adopt here is that active motoric engagement may contribute to the task of visual shape learning. Specifically, we aim to explore whether engagement in tracing of shapes facilitates their visual processing and promotes their visual discrimination, and to elucidate the mechanisms responsible for this potential facilitation. We will do so by examining the independent and additive contribution of different aspects of motor engagement to shape learning.

The results provided by our project can serve didactic practice in STEM (science-technology-engineering-mathematics) for designing more effective approaches to the development of spatial cognition and geometrical conceptual understanding. A particularly compelling future clinical application will be for developing research-driven visual training programs that can help individuals with perceptual challenges learn spatial concepts. Of particular interest to us are interventions for helping congenitally blind patients after sight restoring treatment (‘Project Prakash’) to strengthen association between movement and visual outcome and improve their learning of visual shapes and patterns.

**Suggested reviewers:**

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Tommasso Vecchi - http://cognition.unipv.it/vecchi/

geroin Smith - motor control

Jeroen B.J. Smeets

**Broader Impacts Statement**

**Investigating the contribution of the motor system to visual shape discrimination**

Prof. Roy Mukamel (TAU), Prof. Pawan Sinha (MIT), Prof. Flip Phillips (RIT)

BSF application number

*Scientific value:*

Our interdisciplinary collaboration provides a comprehensive exploration of the role of motor engagement in visual shape learning. The use of a well-designed stimulus set and of tailored analysis methods will allow us to identify the components and processes that support visual learning in adults. We expect this to promote the understanding of how visual-motor interplay and integration contribute to learning.

*Stimuli and data sharing:*

Our novel approach to stimuli construction (of shapes with parametric differences which are validated against human perception) and the comprehensive database built through our experiments will be made available to other researchers. We believe that it will serve as a valuable resource; the stimuli construction method would be useful in any setting in which explicit, and parametric, control over the visual similarity of shapes is required, whereas the dataset could be used to test hypotheses regarding associations between motor skill development and visual shape learning.

*Practical implications:*

Expected conclusions regarding the effectiveness of harnessing the motor system to boost processing of visual stimuli hold potential practical implications. They will provide an empirical evaluation of a commonly employed approach in education involving shape reproduction for teaching geometric shapes1,2 and may open avenues for training regimens utilizing effects uncovered by our investigation, such as the effect of using the non-dominant hand. Of particular interest to us is the potential contribution to the rehabilitation of individuals with perceptual challenges, specifically to design research-driven interventions for supporting visual recovery of congenitally blind patients after sight-restoring treatment (‘Project Prakash’)3.

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