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Movements or Memorization: A Trade-Off in a Copying Task

Author

Luo, Chuan

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Movements or Memorization: A Trade-Off in a Copying Task

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Chuan Luo

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Dissertation Committee:

Dr. John M. Franchak, Chairperson
Dr. Elizabeth L. Davis
Dr. Kalina J. Michalska

The Dissertation of Chuan Luo is approved:

Committee Chairperson

University of California, Riverside

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To my parents for all the support.

ABSTRACT OF THE DISSERTATION

Movements or Memorization: A Trade-Off in a Copying Task

by

Chuan Luo

Doctor of Philosophy, Graduate Program in Psychology
University of California, Riverside, September 2023
Dr. John M. Franchak, Chairperson

The aim of the dissertation is to investigate how people trade off between expending motor effort and memorization effort when visually exploring in different directions to gather information. Specifically, Chapter 2 studied how the motor effort of eye-head-body movements and memorization difficulty affected the motor-memory trade-off in a copying task. Chapter 3 studied how people adjusted the motor-memory trade-off after repeated practice with the task. Lastly, Chapter 4 studied whether inducing people to test a different strategy led to discovery and later adoption of a more efficient strategy. Each chapter examined both the copying strategies (i.e. the trade-off between using more motor effort versus more memory) and the eye-head-body coordination underlying the task. Results showed that participants expended more motor effort when the eye-head-body movements to make gaze shifts were less effortful and when the information was difficult to remember (Chapter2); participants used more memory after repeated practice with the task (Chapter 3); exposing participants to test a different strategy led them to adopt a memory-based strategy (Chapter 4). Overall, participants coordinated their eyes, head, and body differently according to the task conditions such as angle and external restriction. They also changed the eye-head-body coordination to decrease total motor cost over the course of doing the task. The findings suggested that people are adaptive in trading off between motor effort and use of memory.

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Chapter 1

Introduction

People need both motor and cognitive abilities to complete almost every task, but they can choose to trade off the use of them in some situations. A *trade-off* means using one ability more to compensate for using the other less. Previous studies have demonstrated that people trade off between expending motor effort and memorization effort when completing a copying task that requires looking in different directions to gather information [9, 26, 55, 70, 93]. The aim of the dissertation is to investigate how people adjust the motor-memory trade-off and the eye-head-body coordination underlying the copying task. Across three studies, a primary goal was to understand whether people navigated the trade-off *efficiently*. More memorization can allow people to complete the task more quickly by reducing the need to look multiple times. In particular, more use of head and body rotations to look can decrease efficiency. Thus, the studies examined how people spontaneously choose more versus less efficient strategies, and identify what factors potentially lead to a change in strategy.

Specifically, Chapter 2 studied how the motor effort of eye-head-body movements and memorization difficulty affected the motor-memory trade-off. Chapter 3 studied how people adjusted the motor-memory trade-off after repeated practice with the task to understand whether task learning leads to adopting more efficient strategies. Lastly, Chapter 4 studied whether inducing people to test a different strategy led to discovery and later adoption of a more efficient strategy. Each chapter examined two sets of behaviors—the *motor-memory trade-off* and the *eye-head-body coordination*. In the following, I will first review how the motor-memory trade-off has been studied using the copying task. Second, I will review the effects of repeated practice and strategy exploration, and discuss how those findings might be applied to the motor-memory trade-off. Last, I will highlight the importance of capturing the eye-head-body coordination and relating it to the motor-memory trade-off.

1.1 Movement or Memorization: A Trade-off in a Copying Task

Suppose you are copying information from a board to your notebook. Depending on whether the board is located close or far, you may choose different ways to gather the information. If the board is just in front of you, you may choose to move the eyes, head, and body frequently (i.e. expending more motor effort) to copy the information. If the board is behind you, you may hold more information in memory to avoid looking back and forth multiple times.

This example illustrates a trade-off where people may choose to use more motor effort or memory to compensate for using the other less according to the task conditions. Past work has investigated this motor-memory trade-off in a copying task [9]. In the study, participants were instructed to copy the models composed of 8 blocks. How participants visually explored the models to gather information was recorded, which included the number of times they moved their eyes, head, and body to look at the model for a trial, and the mean duration of the model looks. The number of looks was used as a measure of the motor effort expended by participants. The more frequently participants looked at the models, the more motor effort they expended. The mean duration of model looks was used to indicate the use of memory, assuming participants were memorizing the information while looking. Results showed that participants looked at the models very often with short duration. They tended to copy 1 block at a time. That is, they were willing to expend more motor effort by moving their eyes, head, and body frequently to minimize the information they held in the memory. This copying strategy was not efficient as participants spent excessive time looking back and forth. Would people change the strategy to use more memory to reduce frequent looking?

Recent work found that people adjust the trade-off to task constraints. For example, Draschkow and colleagues varied the angle of the models from 45° to 135° [26]. Results showed that participants decreased the frequency of moving their eyes, head, and body to look at the models at larger angles. Instead, participants spent longer looking at the model each time to remember the information. That is, when larger, more effortful movements were required, people chose to use more memory to reduce motor effort. However, the increase in use of memory was minimal. Participants still looked more frequently than was necessary.

In addition, other task constraints such as the accessibility and predictability of the to-be-gathered information [8, 63, 27], the time constraint to complete the task [68], and the cost of making errors [68, 106] may affect the motor-memory trade-off. This dissertation focused on the effects of the motor effort required to move the eyes, head, and body to gather information and the memorization difficulty of models (Chapter 2). This dissertation also studied how people adjust the motor-memory trade-off to improve efficiency in a given condition after repeated practice (Chapter 3) and strategy exploration (Chapter 4).

1.1.1 Effect of Repeated Practice

How might people improve efficiency when trading off between motor effort and memory within task? One possibility is that people might spontaneously adjust the motor-memory trade-off for higher efficiency after repeated practice with the task. Previous literature suggested that with practice people improved efficiency in a variety of memory, problem-solving, and decision-making tasks [108, 79, 80, 119, 28, 64, 108, 76, 100, 89]. For instance, participants responded faster and faster in recognizing and generating words after multiple trials of memory tasks [108, 79, 80, 119, 28]. Higher predicting accuracy was achieved as participants practiced more in a gambling game [100]. Less time was needed to solve math problems if participants were exposed to similar problems before [89]. But how do people improve efficiency after repeated practice? Do they improve by executing the same strategy more efficiently? Or do they change the strategy?

Some past work suggested that people may stick with their initial strategies after repeated practice [129, 90]. In a memory test, participants were presented with arrays of word pairs and asked to determine as quickly as possible if the target word pair matched one of the pairs in the arrays [129]. Results showed that participants visually checked the arrays frequently to compare with the target after multiple trials, although they could possibly memorize the arrays and compare with the target from memory. In another reaching task, participants were asked to choose one strategy from two options before the start of each trial [90]. Although their decisions on the strategy in trial 1 were arbitrary, participants did not tend to change them in later trials. One explanation was that adjusting strategies may compete for common cognitive resources such as attention, information processing, and executive functions, which may slow down the on-going motor performance [90].

Would people change their strategy—using more memory in the copying task? Since the copying task incurs both perceptual-motor and cognitive demands, strategy change might be expensive. Moreover, with multiple degrees of freedom, participants might explore various ways of improving their efficiency. People could maintain a similar number of times looking at the model (keeping memory constant), but change the way they coordinate the eyes, head, and body to use less costly movements. Or, people could change strategies by using more memory and fewer looks to the model. Either possibility (or both in combination) could improve efficiency. The change in strategies has to be efficient enough in saving effort to compete with the motor system. It remains unknown whether people choose to use more memory with experience over time.

1.1.2 Effect of Strategy Exploration

Strategy change may depend on people's willingness to explore strategies. Past work suggested that compared to young children, adults are reluctant to explore different strategies [41]. In the study, participants made perceptual judgments whether they could squeeze through a doorway while wearing a backpack. They were allowed to explore the doorway freely. However, unlike young children who tried different ways to squeeze through the doorway, some adults never practiced, resulting in poor perceptual judgments. The findings suggested that adults tend to avoid taking risks or making mistakes.

Past work also showed that people may discover and adopt the most efficient strategy after being exposed to all possible strategies [68]. In the study, participants copied information from one program to another on a computer. They first went through no-choice trials where they were constrained to use certain strategies to copy the information. Afterwards, participants went through choice trials where they were allowed to use any strategy they preferred. Results showed in the choice trials, participants chose the strategy that previously produced the highest correct copying rate in the no-choice trials. The findings suggested that people are sensitive to the strategy efficiency but have to be induced to explore different strategies in the first place.

How would people be willing to explore strategies in the copying task where the movements of eyes, head, and body are required to visually explore the information? Would they discover and adopt the more efficient strategy after being exposed to a different strategy? In Chapter 4, we increased the motor cost of eye-head-body movements by head restriction and tested if it induced strategy change, and produced carry-over effects after the head restriction removed.

1.2 Eye-Head-Body Coordination in the Copying Task

Each decision to shift eye gaze from one location to another means selecting how to coordinate multiple effectors, suggesting that there are multiple degrees of freedom to control. For example, shifting gaze 20º horizontally can be accomplished by a 20º eye movement with no movements of head or body, a 10º eye movement with a 10º head movement and no body rotation, or a 5º eye movement with a 5º head movement and 10º body rotation (among many other possibilities). How people choose to coordinate their effectors directly impacts the motor cost. Each lower-effort eye movement and higher-effort head and body movements expends different amounts of energy. As I will review, the coordination of eyes, head, and body can be complex.

1.2.1 Characteristics of Eye, Head, Body Movements

Prior work treated motor effort as a linear or categorical variable [9, 26, 55, 70]. In one example, Draschkow and colleagues varied the motor effort by placing models at the angle of 45°, 90°, and 135° [26]. In another study, the motor effort was manipulated by varying walking distance between the workspace and model [59]. However, the eye-head-body coordination is non-linear [43, 42, 86, 123, 45, 48, 120]. First, the eyes, head, and body have different biomechanical properties [86, 67, 60, 123, 3, 126, 51]. For example, eye movements are quick with smaller range of rotation whereas the head and body movements are slow with larger range of rotation [86, 67, 60, 123, 3, 126, 51]. As a result, eye movements are less effortful and cost less energetically compared to head and body movements [122].

Second, people may coordinate their eyes, head, and body differently in everyday tasks compared to in lab studies. For example, as shown in lab studies, people can horizontally rotate their eyes to as large as about 55° and rotate their head to ±90° [58, 126]. But people do not tend to move their eyes and head near the motor limit in everyday tasks. Instead, they move the eyes, head, and body to make small amplitude gaze shifts [125, 101, 45, 69, 91, 30].

Thus, it was unclear in the previous studies how the manipulation of angle or distance changed the motor effort (i.e. eye-head-body movements). The current studies attempted to address this limitation by measuring the actual movements of the eyes, head, and body when viewing the models at a wide range of angles in the copying task. Understanding the relative contributions of low-effort effectors (eyes) versus higher-effort effectors (head and body) will help explain why effort varies between different angles of rotation, and may provide insight about how participants select how often to make gaze shifts in different circumstances.

1.2.2 Learning to Coordinate Eye-Head-Body More Efficiently

In addition to capturing the real-time eye-head-body coordination, the studies aimed to examine the changes in eye-head-body coordination after repeated practice. How might participants change their eye-head-body coordination over the course of doing the copying task for multiple trials? First, participants might improve the speed of moving their eyes, head, and body. Previous studies showed that participants decreased the latency of movements, moved faster, and had less errors in the key-pressing, throwing, and kicking tasks [20, 19, 96, 21, 53]. It is possible that participants would rotate their eyes, head, and body more quickly in the copying task to improve efficiency with practice.

Second, participants might change the eye-head-body coordination with repeated practice. A prior study showed that participants restricted head movement at the beginning of a large-scale searching task but learned to coordinate the eyes and head later in the task [33]. It is possible that in the copying task participants might increase the proportion of eye and head movements to reduce costly body movements thus improving higher efficiency. But it remains unknown whether people would execute the same eye-head-body coordination or change the proportion each segment contributes when making gaze shifts after repeated practice.

It is possible that people may not discover the most efficient eye-head-body coordination spontaneously after practice. Does inducing people to explore different eye-head-body coordination lead to discovery and adoption of more efficient eye-head-body coordination? What is the effect of eye-head-body alteration on the motor-memory trade-off? Does it explain the strategy change in the copying task? The dissertation explored if head restriction is a successful manipulation on the eye-head-body coordination and whether it induces coordination changes after the head restriction removed.

In sum, this dissertation investigated how people trade off motor effort and use of memory depending on task constraints, and how they adjust the motor-memory trade-off for higher efficiency after repeated practice and strategy exploration. Besides the copying strategies, the underlying eye-head-body coordination were examined to better understand the effect of motor cost on the motor-memory trade-off.

Chapter 2

Eye-Head-Body Coordination in the Motor-Memory Trade-Off

2.1 Abstract

Previous studies have demonstrated that people trade off between expending motor effort and memorization effort when completing a copying task that requires looking in different directions to gather information. When information is easy to gather with minimal movement, people choose to look more frequently and rely on less on memorization, however, they reduce motor effort and rely on memory more when looking requires larger (and more effortful) shifts of gaze. This paper investigated the eye-head-body movements that guided looking as well as participants' trade-off between using motor effort and memory in a copying task. We add to prior work by characterizing the coordination between eyes, head, and body required to look at targets at different angles. In the task, participants copied models onto

a board while wearing a mobile eye tracker that measured eye rotations and motion sensors that measured head rotations. We manipulated the angle of the model relative to the participant and the memorization difficulty of the models. Results showed that the eye movements contributed more to small gaze shifts but the head and body contributed more as the angle of the target increased (requiring larger amplitude shifts of gaze). Participants chose to look frequently when models were adjacent to the workspace, but chose to rely more on memory for models that required greater shifts of gaze. Memorization difficulty affected the trade-off such that participants used more memory when the models were easy to remember. We discuss how participants' decisions to look versus remember may depend on the contribution of eyes, head, and body to shift gaze by varying amplitudes.

2.2 Introduction

Suppose you are cooking an unfamiliar meal and you need to follow the recipe. Will you turn to look at the recipe at each step to avoid taxing your memory, or will you memorize several steps during each look at the recipe to reduce the effort incurred by looking multiple times? It may depend on how close recipe is to the counter. If you only need to glance to the side of the counter to see the recipe, you may choose to look more frequently. If you have to turn completely around to see the recipe pinned to the fridge, you may prefer to memorize more steps at a time.

This example illustrates that people trade off the use of motor and cognitive abilities depending on task conditions. Previous studies have shown that people's trade-off between using more motor effort or more memory depends on the degree of effort required to turn the eyes, head, and body to gather information [85, 62, 55, 59, 70], the accessibility and predictability of the to-be-gathered information [8, 63, 27], the time constraint to complete the task [68], the cost of making errors [68, 106], and the exposure to prior training [106]. In this paper, we will focus on how motor effort and memorization difficulty affect the motor-memory trade-off and the coordination of eye, head, and body movements to visually explore in different directions.

In a foundational experiment, Ballard and colleagues devised a block-copying task to examine the motor-memory trade-off [9]. In the block-copying task, participants were asked to copy models consisting of eight blocks onto a nearby blank board (i.e. workspace). Results showed that participants picked up one block at a time, looked at the model where the block was located, and then placed the block on the workspace. They followed the same sequence—look, pick up, look, place—to copy the blocks. The finding suggested that participants were willing to expend motor effort to look at the model each time rather than rely on memory to copy the models. However, in another study [8] found that if the models were only present for 10 s, participants were actually able to remember the locations of 4 blocks at a time and copied them correctly from memory. But participants did not do so voluntarily when given a choice.

Recently, [26] manipulated the motor effort required to visually inspect the model by varying the angle needed to turn to look at the models by placing them at 45°, 90°, and 135° around the participants. They measured how many features (e.g. the identity and/or location of one or multiple blocks) participants remembered in one look. Results showed that participants only memorized 1-2 features each time they looked at the model, and the number of features memorized remained similar as the angle increased. That is, the increase in memorization in response to the increased motor effort was very small. People were reluctant to use memory even though using memory could improve efficiency by reducing the number of model looks (which reduces the total amount of motor movement).

A limitation in past work was how motor effort was operationalized. In previous studies, motor effort was considered as either a binary (e.g. more or less) or linear variable (e.g. ranging from 45° to 90° and from 90° to 135°). But simply increasing the angle may not result in equal, linear change in motor effort. As we will review, the coordination of eyes, head, and body can be complex.

Indeed, the motor effort to look depends on how the eyes, head, and body are coordinated to shift gaze [43, 42, 86, 123, 45, 48, 120]. The oculomotor range of human eyes is ±55° horizontally [58, 126], which means that people can only look at things within 55° to either side without also moving the head or body. But people do not tend to make eye movements near the oculomotor limit unless head movement is restrained, such as in laboratory situations. Instead, people move both the eyes and head (and even body slightly) to make small amplitude gaze shifts in everyday tasks [125, 101, 45, 69, 91, 30]. But, as the gaze shift angle increases, the head and body make larger contribution to the gaze shifts [47, 67, 45, 109, 120].

How might changing contributions of the eyes versus head versus body alter the motor effort of a gaze shift? First, the eyes, head, and body movements have different biomechanical properties. Eye movements are quick with smaller range of rotation whereas the head and body movements are slow with larger range of rotation [86, 67, 60, 123, 3, 126, 51]. Second, eye movements cost less energetically compared to head and body movements [122]. It is possible that compared to eye movements, head and body movements may greatly change people's willingness to use motor effort versus memory.

Thus, it was unclear in the previous studies how the manipulation of angle changed the motor effort (i.e. eye-head-body movements). As a result, in the current study we tracked the movements of eyes, head, and body in the block-copying task to observe the eye-head-body coordination to view models varying from 45° to 180°. We aimed to measure the actual movements of the eyes, head, and body when each gaze shift was made in a motor-memory trade-off task. Understanding the relative contributions of low-effort effectors (eyes) versus higher-effort effectors (head and body) will help explain why effort varies between different angles of rotation, and may provide insight about how participants select how often to make gaze shifts in different circumstances.

In addition to motor effort, some previous studies also manipulated memorization difficulty by designing different patterns of models to test the effect of memorization difficulty on the motor-memory trade-off [85, 59]. The findings from the previous studies were mixed. In [85], two types of models were generated with one type organized into one configuration whereas the other as two configurations (with space in between). Both types were composed of 6 blocks of 3 different colors. No effect of memorization difficulty was found in their study. However, in [59], the "easy" and "difficult" models (both composed of 6 blocks of 6 different colors) depended on how adjacent blocks were connected—the adjacent blocks shared a full edge in the easy model, whereas shared a half edge or a corner point in the difficult model. They found a significant main effect of memorization difficulty on the motor-memory trade-off: the more difficult, the more motor effort was spent by the participants to look at models.

Is it possible that the mixed results were due to the fact that the models were made too difficult so that the participants minimized the use of memory even for the ”easy” models? Thus, in the current study, we enlarged the difference between the easy and difficult models by making the easy model easier to remember to investigate the effect of memorization difficulty. Specifically, the difficult model was equivalent to the models used in the foundational study [9] consisting of 8 blocks of various colors. The easy model contained 8 blocks of the same color. The same-colored models were easy because the participants only needed to remember the location of the blocks, whereas the multi-colored models were difficult as both the color and location of the blocks to be remembered. With decreased memorization difficulty in the easy model, the participants might adopt a different trade-off by using more memory and reducing the number of times they look at the model. Crossing memorization difficulty with the angle of the model allowed us to test if memorization difficulty interacted with motor effort, or whether memorization difficulty and motor effort had independent effects on visual exploration.

2.3 Current Study

Although motor effort has been identified as a factor that affects the motor-memory trade-off, little is known about the underlying eye-head-body movements that guide looking. In the current study, we first examined how motor effort and memorization difficulty affected people’s willingness to use more movement or memory in the block-copying task [9]. Second, we investigated how the eyes, head, and body coordinated to visually explore models at different rotations.

In the task, we manipulated two independent variables: 1) motor effort, by placing the models at 4 different angles on each side of the participants (45°, 90°, 135°, and 180°); and 2) memorization difficulty, by varying whether the model to be copied contained a set of blocks consisting of either one color or multiple colors. The two independent variables were fully crossed. We aimed to investigate how the varying motor effort and memorization difficulty affect participants' trade-off between motor and memory use.

To answer the first question on how motor effort and memorization difficulty affect the motor-memory trade-off, a head-mounted eye tracker worn by the participants determined when participants looked at the models, allowing us to calculate two dependent variables. The first dependent variable was how many times the participants looked at the models in the trials (number of looks), which indicated the motor effort spent by the participants to view the model. The greater number of looks meant the participants moved the eyes, head, and/or body more frequently to look at the model. The second dependent variable was the mean duration of a model look in the trials (look duration). The longer they looked at the models meant they spent longer time memorizing the models during each look. We hypothesized that as the angle of the models increased, participants would move their eyes, head, and body less frequently to look at the models, but the duration of each look would increase as they needed to encode the models in memory. However, when models were more difficult to memorize, the participants might spend less time memorizing the models each time, instead choosing to look at the models more frequently to acquire the information needed to copy.

To answer the second question on the eye-head-body coordination, we measured the eye-head-body rotations when participants looked at the models at different angles. Specifically, we calculated the eye rotation within the head during the model looks using the head-mounted eye tracking data. Two inertial measurement units (IMUs) were placed at the participants' forehead and the base of their neck to measure the head rotation within the body during the model looks. To estimate the body rotation relative to the space, we subtracted the sum of eye and head rotations from the angle of models. Knowing the eye, head, and body rotations, we examined the absolute degrees the eyes, head, and body moved to look at the models and their relative proportion in accomplishing the rotation. We hypothesized that as the angle of models increased, the eye, head, and body rotations would all increase, but by different rates. By each increase of 45° in the models, the body rotation would increase the most while the head rotation would increase less and the eye rotation the least. That is, body movements would account for an ever-larger proportion in the rotation as the participants needed to look at the models at larger angles.

2.4 Method

2.4.1 Participants and Design

Twenty-eight college students (14 males, 14 females, *M* age = 19.7 years, *SD* = 1.91) participated in the study. All participants had normal or corrected to the normal vision and were not color blind. One participant was left-hand dominant and the remaining participants were right-hand dominant. They were recruited from the introductory psychology class at the University of California, Riverside and received course credit for their participation in the study. Participants described their ethnicity as Hispanic/Latinx (14) or not Hispanic/Latinx (13); one participant chose not to answer. Participants described their race as Black (2), White (4), More than One Race (4), Asian (11), Pacific Islander (1), and Other (4); two chose not to answer. Four other participants were run but excluded from the study due to technical problems affecting the eye tracking and/or motion tracking (e.g. poor pupil detection, motion sensors stopped recording). A sensitivity analysis indicated that the final sample size had 95% statistical power to detect an medium effect size of d = .52 for the analyses.

This study used a within-subject design where each participant completed 16 trials of the model-copying task in a 60-min session. Two within-subject factors were the angle of the model (45°, 90°, 135°, or 180°) and the difficulty of the patterns (same-colored or multi-colored). Four random orders of the trials (2 instances of each angle-difficulty pairing) were generated and alternately used among participants.

2.4.2 Apparatus

The experimental setup is shown in Figure 4.1. Participants stood in front of a music stand which held the *workspace*: an empty 4 × 4 grid with 8 magnets provided for participants to copy the model. The magnets were placed on the side of the grid corresponding to the participant's dominant hand. The *model* was displayed on another music stand which was positioned at the angle of 45°, 90°, 135°, or 180° to the left or right side of the participant. The distance from the participants to the workspace was 35.56 cm

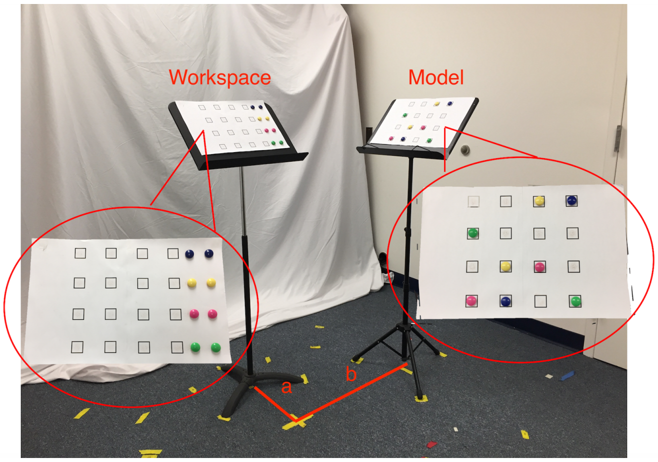


Figure 2.1: An example trial in which the multi-colored model was positioned at 90° on the right side.

(the line ‘a’), and was 66.04 cm to the model (the line ‘b’). The height of the workspace and model were adjusted to the participant’s chest level. The models had two levels of difficulty: the easy level was composed of 8 magnets of the same color (green, blue, pink, or yellow); and the difficult level was composed of 8 magnets of 4 different colors with 2 magnets each color. Two wall-mounted security cameras (on the participants’ left and right sides) recorded the third-person view videos.

To capture eye movements, participants wore a Positive Science head-mounted eye tracker (Figure 3.2). The eye tracker has two cameras: a *scene camera* positioned over participants’ right eye recording the participants’ first-person field of view, and an *eye camera* that points to the participants’ right eye and records the eye movements. The two cameras are mounted on a lightweight eyeglass frame. The videos recorded by the two cameras (sampling rate 30 Hz) were streamed to a recording device attached to the shoulder band worn by participants.

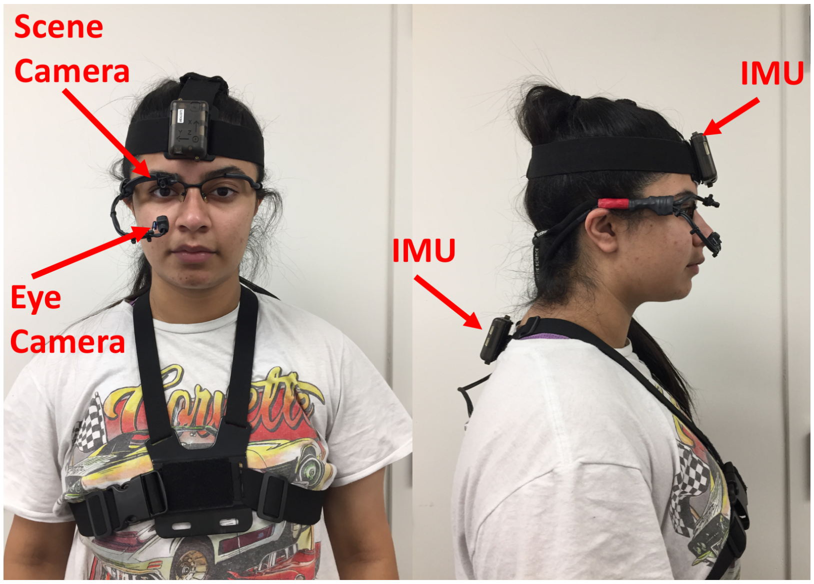


Figure 2.2: Participants wore a head-mounted eye tracker, which has an eye camera and a scene camera, and two IMUs placed at the forehead and the base of neck were attached to a headband and a shoulder band.

To capture head movements, participants wore two wireless STT Systems IWS inertial measurement units (IMUs) (dimensions: 56 × 38 × 18 mm, 46 g): one on the forehead (attached to a head band), the other on the neck (attached to a shoulder band) at the C7 vertebrae (Figure 3.2). The IMUs streamed acceleration and gyroscope data at a rate of 400 Hz over WiFi to the STT software installed on a laptop, which recorded the data.

2.4.3 Procedure

In the 1-hour long session, participants were instructed to complete the model-copying task, before and after which they completed brief calibration for the eye tracker and IMUs.

Calibration and Synchronization for the Eye Tracker and IMUs

After giving consent, participants put on a shoulder band, a head band, and the eye tracker. The experimenter adjusted the cameras of the eye tracker to ensure the scene camera would capture the participant's first-person field of view and the eye camera would capture the pupil and corneal reflection no matter how participants moved their eyes. The experimenter attached the IMUs to the headband and shoulder band worn by the participants and ensured they were at the correct positions and orientation.

To calibrate the eye tracker, participants stood 35 cm away from a cardboard poster (76 cm × 51 cm), which was put on the music stand. Nine targets (2.5 × 2.5 cm) were drawn on the board: 4 at the corners, 4 at the midpoints of each edge, and 1 at the center. Participants were asked to move their eyes to look at specific targets while keeping their head still. The eye tracker measured the rotations of eyes while participants were looking at different targets in the field of view and determined the gaze direction in pixels relative to the scene camera video. The same calibration procedure was repeated in the middle and end of the model-copying task to ensure the accuracy of eye tracking throughout the session.

To calibrate the IMUs and to synchronize with the eye tracking data for subsequent analyses, participants were asked to look forward, keep the chin parallel to the floor and still for a while, and then quickly turn the head to the left and right. These motions created identifiable moments in the IMU data to be synchronized with the eye tracking data. The experimenter checked the visualization of the IMUs data on the software to ensure it showed the correct motions.

Model-Copying Task

Participants completed two practice trials and 16 experimental trials of the model-copying task. Sixteen different configurations of the model patterns (8 same-colored and 8 multi-colored) were randomly created by a computer script. One same-colored and one multi-colored patterns were randomly assigned to each model position (4 angles × 2 sides). In each trial, participants were required to copy the model correctly while standing at a designated spot on the floor (the wrongly copied trials were excluded from the data analyses). They were also required to pick up one magnet at one time with the dominant hand. They faced toward the workspace at the beginning of each trial but were allowed to freely turn their head, body, and feet to look at the model as many times as they needed while copying the model. They were reminded to close their eyes while the experimenters changed the model between trials.

2.4.4 Data Processing and Analyses

First, the eye rotation in each frame of the scene videos (in unit of pixels) was calculated from the eye and scene videos recorded by the eye tracker using the software Yarbus (Positive Science). The time series of horizontal eye rotation in pixels were then converted to degrees based on the camera's horizontal field of view and lens correction, as in [45].

Second, the acceleration and gyroscope data recorded by the IMUs were used to calculate the time series of horizontal head rotation in degrees relative to the base of the neck by the software iSen (STT Systems).

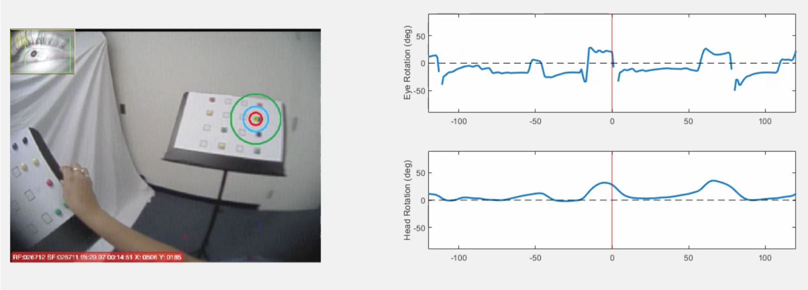


Figure 2.3: The eye tracker videos were synchronized with the time series of horizontal eye and head rotations. Left: One frame taken from the eye tracker videos (the eye video was imposed over the scene video on the top left corner). The bulls-eye showed the participant's gaze landed on the model which was positioned at 90° to the participant's right hand side. Right: The time series of eye (upper) and head (lower) rotations in degrees, with positive values on the y-axis indicating rotations to the observer's right. The x-axis is time with positive values indicating the future and negative values indicating the past. The red vertical lines mark the current time (0), which corresponds to the video frame shown on the left.

Third, to synchronize the eye tracking and IMU data, the experimenter identified the sharp head turns participants made during calibration in the time series of IMU data and the corresponding moments in the scene videos (quick shifts of field of view). The experimenter marked down the times of the head turns and the frame numbers in the videos and then converted the times series to the unit of frames in a Matlab script. Figure 2.3 showed the synchronized data of eye, head rotations and the eye and scene videos.

After synchronization, for each frame of the trials in the scene videos, two independent coders tagged each instance of gazing at the model. The inter-rater reliability was 95.4%. If the participants' eye gaze fell within the area of model in the field of view for at least 2 frames (allowing 1 frame off or a blink in between), a *model look* was defined (Figure 2.3). Once the model looks were defined, we calculated five outcome variables for different trials:

1. *Number of looks*: the total number of model looks in a trial. The larger the number of looks is, the more frequently the participants moved their eyes, head, and body to look at the models (expending greater effort).

2. *Look duration*: the duration of an average model look in a trial. This variable was calculated by calculating the mean duration of all model looks in a trial (in unit of frames then converted to seconds). Longer average look durations suggest that participants spent longer in memorizing the models.

3. *Eye rotation*: the mean of the horizontal eye rotation during model looks in a trial. Note that the absolute values of the eye rotation were used in the calculation to avoid the opposite signs of the degrees (positive if to the right and negative if to the left) cancelling each other out.

4. *Head rotation*: the mean of the horizontal head rotation during model looks in a trial. Similarly, the absolute values of the head rotation were used in the calculation.

5. *Body rotation* was estimated by subtracting eye and head rotations from the angle for the trial and then taking the absolute values.

For statistical analyses, linear mixed-effect models (LMMs) were first applied to test the effects of model side (2 levels, left and right), angle (4 levels, 45°, 90°, 135°, 180°), and difficulty (2 levels, easy and difficult) on the number of looks and look duration using the *lme4* [11] package in R [110]. The side, angle, and difficulty were included as fixed effects and participant as a random effect in the LMMs (random slope models failed to converge). Results showed there was no interaction between side and angle/difficulty. More importantly, we were mainly interested in how angle and difficulty affected the motor-memory trade-off and eye-head-body movements. Therefore, we collapsed side and only tested the effects of angle and difficulty in the analyses reported below.

To understand the effects of angle and difficulty on the eye-head-body coordination, two 3-way LMMs predicting the rotation (in degree) and proportion (%) separately were calculated with angle, difficulty, and segment (eye, head, and body) as the independent variables. For all analyses, ANOVAs were used to test significance of main effects and interactions from the LMMs using the *lmerTest* package in R [83]. Degrees of freedom were determined by the Satterthwaite approximation [117, 92]. Follow-up pairwise comparisons used the Holm-Bonferroni correction to adjust for multiple comparisons.

2.5 Results

2.5.1 Motor Effort and Memorization Difficulty Affected Motor-Memory Trade-Off

The number of looks decreased as the angle of the model became larger (Figure 2.4A). That is, the participants moved their eyes, head, and body less frequently to look at the model if the models were positioned at larger angles that required greater rotations. Instead, they spent longer to look at and memorize the models (Figure 2.4B). However, as the model became difficult to remember, participants relied on more frequent eye-head-body movements to gather information about the models rather than using memory. Descriptive statistics are shown in Table 2.2.

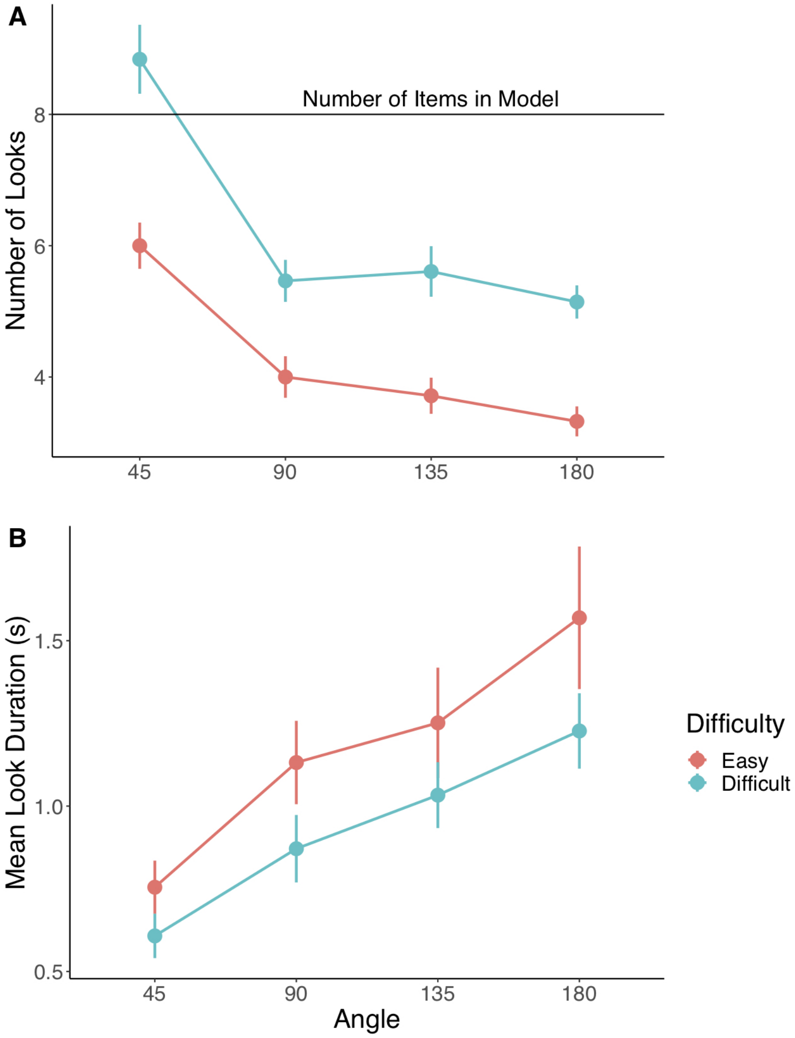


Figure 2.4: The number of looks (A) and mean look duration (B) across angle and difficulty.

Table 2.1: Summary of LMM results predicting the number of looks and look duration from angle and difficulty.

		Number of Looks			**Look Duration**		
	df	*F*	*p*		*F*	*p*	
Angle	3	77.38	<.001	***	35.09	<.001	***
Difficulty	1	145.01	<.001	***	22.91	<.001	***
Angle × Difficulty	3	3.35	.020	*	.59	.620	n.s.

**p*<.05, ***p*<.01, ****p*<.001

Table 2.2: Descriptive statistics (*M* and *SD*) for the number of looks and look duration (in second) by angle and difficulty.

	Number of Looks		**Look Duration**	
	Easy	Difficult	Easy	Difficult
45°	6.00(1.86)	8.84(2.78)	.75(.43)	.61(.35)
90°	4.00(1.67)	5.46(1.69)	1.13(.67)	.87(.54)
135°	3.71(1.46)	5.61(2.04)	1.25(.88)	1.03(.53)
180°	3.32(1.18)	5.14(1.34)	1.57(1.12)	1.23(.60)

The results of the LMM predicting the number of looks showed significant main effects of angle and difficulty and a significant interaction effect (Table 2.1). To follow up on the angle × difficulty interaction, pairwise comparisons between adjacent angles within each difficulty condition suggested that the number of looks at 45° was significantly greater than that at 90° for the easy ($t(188) = 6.104$, $p < .001$) and difficult levels ($t(188) = 10.300$, $p < .001$). The larger drop in the number of looks from 45° to 90° at the difficult level compared to the easy level resulted in the angle × difficulty interaction. There was no difference in the number of looks between 90° and 135° or between 135° and 180° for either difficult level. Nevertheless, participants looked at the model more frequently in the difficult condition at every angle.

The results of the LMM predicting mean look duration only showed significant main effects of angle and difficulty (Table 2.1), indicating that participants looked at the models for longer period of time when the models were at larger angles and when models were easy to remember. The descriptive statistics are shown in Table 2.2. Follow-up pairwise comparison between adjacent angles showed an increase in the look duration from 45° to 90° ($t(188)$ = -4.538, $p < .001$), from 90° to 135° ($t(188)$ = -1.997, $p = .047$), and from 135° to 180° ($t(188)$ = -3.533, $p = .001$). Thus, unlike number of looks which changed from 45° to 90° but not beyond 90°, look duration showed progressive increases with each 45° increase in model angle.

2.5.2 Eye-Head-Body Coordination Differed Across Angles

As Figure 2.5A shows, the eye, head, and body rotations all increased as the angle of the models increased, but each segment (eyes, head, or body) increased at different rates. The body rotation increased most and sharply; the head rotation first increased quickly then slowed down; whereas the eye rotation remained almost the same across the 4 angles. Proportionally, the contribution of the eye movement to the gaze shifts decreased as the angle increased (Figure 2.5B). The contribution of the head movement first increased and then slightly decreased. The contribution of the body movement, however, kept rising. It implied that the participants mainly moved the eyes to look at the models at small angles. As larger movements were required to look at the models, the participants then relied more on head and body movements.

The results of the LMMs (Table 2.3) predicting the rotation showed main effects of angle (4 levels: 45°, 90°, 135°, 180°) and segment (3 levels: eye, head, body) and an interaction between angle and segment. To follow up on the interaction (Table 3.3), pairwise

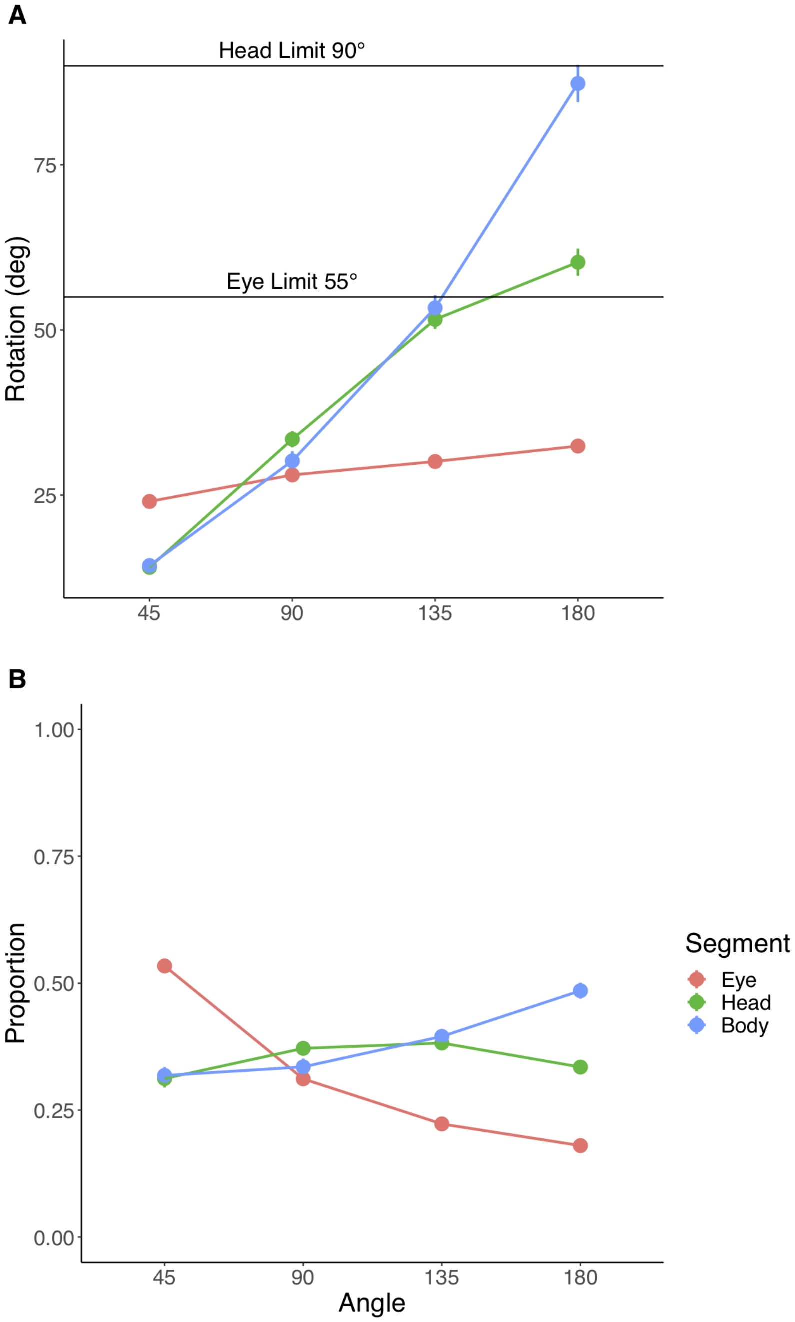


Figure 2.5: A: The average eye, head, and body rotations at different angles. B: The proportion that the eye, head, and body movements contributed to the gaze shifts as the angle increased. Note that the proportions were calculated at the trial level, so the sum of mean proportions is not equal to one.

Table 2.3: Summary of LMM results predicting rotation and proportion from angle, difficulty, and segment.

		Rotation			**Proportion**		
	df	*F*	*p*		*F*	*p*	
Angle	3	469.53	<.001	***	12.13	<.001	***
Difficulty	1	.01	.925	n.s.	.03	.862	n.s.
Segment	2	148.82	<.001	***	29.23	<.001	***
Angle × Difficulty	3	.00	1.000	n.s.	.01	.998	n.s.
Angle × Segment	6	99.41	<.001	***	84.60	<.001	***
Difficulty × Segment	2	.21	.807	n.s.	1.09	.336	n.s.
Angle × Difficulty × Segment	6	.38	.895	n.s.	.86	.526	n.s.

*p<.05, **p<.01, ***p<.001

comparisons showed: at 45°, the eye rotation was greater than the head ($t(618) = 4.833$, $p < .001$) and body rotations ($t(618) = 4.700$, $p < .001$) but there was no difference between the head and body rotations ($t(618) = -.133$, $p = .894$); at 90° the eye rotation was slightly smaller than the head rotation ($t(618) = -2.618$, $p = .027$), but there was no difference between the eye and body rotations ($t(618) = -1.027$, $p = .305$) or between the head and body rotations ($t(618) = 1.591$, $p = .224$); at 135° the eye rotation was significantly smaller than the head ($t(618) = -10.418$, $p < .001$) and body rotations ($t(618) = -11.264$, $p < .001$) but there was no difference between the head and body rotations ($t(618) = -.846$, $p = .398$); at 180° the eye rotation was far smaller than the head ($t(618) = -13.355$, $p < .001$) and body rotations ($t(618) = -26.342$, $p < .001$) and the head rotation was smaller than the body rotation as well ($t(618) = -12.987$, $p < .001$). The descriptive statistics are shown in Table 2.5.

The results of the LMMs (Table 2.3) predicting the proportion showed the main effects of angle and segment and an interaction between angle and segment. To follow up

Table 2.4: Pairwise comparisons between segments for each angle.

	Absolute Rotation
45°	Eye > Head = Body
90°	Eye < Head, Head = Body, Eye = Body
135°	Eye < Head, Head = Body, Eye < Body
180°	Eye < Head < Body

Table 2.5: Descriptive statistics (*M* and *SD*) for the rotation (in degree) and proportion by angle and segment. Note that the proportions were calculated at the trial level, so the sum of mean proportions is not equal to one.

	Rotation			**Proportion**		
	Eye	Head	Body	Eye	Head	Body
45°	24.03(4.77)	14.04(5.87)	14.32(5.58)	.53(.11)	.31(.13)	.32(.12)
90°	28.04(5.85)	33.45(9.22)	30.16(11.05)	.31(.06)	.37(.10)	.34(.12)
135°	30.07(5.64)	51.59(10.81)	53.34(14.47)	.22(.04)	.38(.08)	.40(.11)
180°	32.41(7.86)	60.26(15.22)	87.33(20.95)	.18(.04)	.33(.08)	.49(.12)

the interaction (Table 3.5), pairwise comparisons showed that: the proportion that the eyes contributed to the gaze shifts decreased significantly from 45° to 90° ($t(618) = 11.939$, $p < .001$), from 90° to 135° ($t(618) = 4.770$, $p < .001$), and from 135° to 180° ($t(618) = 2.280$, $p = .023$); the proportion of head rotation increased from 45° to 90° ($t(618) = -3.198$, $p = .007$), plateaued from 90° to 135° ($t(618) = -.563$, $p = .574$), and slightly dropped from 135° to 180° ($t(618) = 2.533$, $p = .046$); the proportion of body rotation remained similarly low from 45° to 90° ($t(618) = -.910$, $p = .363$), but increased from 90° to 135° ($t(618) = -3.218$, $p = .003$), and from 135° to 180° ($t(618) = -4.813$, $p < .001$). The descriptive statistics are shown in Table 2.5.

Table 2.6: Pairwise comparisons between angles for each segment based on the proportion of each gaze shift.

	Proportion
Eye	45° > 90° > 135° > 180°
Head	45° < 90° = 135°, 135° > 180°
Body	45° = 90° < 135° < 180°

2.6 Discussion

In this study, we investigated the trade-off between using motor effort to visually explore versus cognitive effort to memorize the model in the block-copying task, and how that trade-off related to eye-head-body movements and memorization difficulty. We found that people coordinated their eyes, head, and body differently to look at models at different angles. The eyes contributed more to small gaze shifts but the head and body contributed more as the gaze shift amplitude increased [47, 67, 109, 120]. This means that even across equally-spaced 45° increases in angle, the increase in effort was not equal because each angle incurred different relative contributions from lower-effort eye movements compared with higher-effort head and body movements. The resulting motor effort of looking influenced how people completed the copying task: they turned their eyes, head, and body more frequently to visually explore the models at 45° compared to the larger degrees (90°, 135°, and 180°); however, they spent longer in memorizing the models as the angle increased in each 45° increment (from 45° to 180°). Memorization difficulty also affected the trade-off such that people used more memory when the models were easy to remember. Memorization difficulty interacted with motor effort for the number of looks such that participants excessively looked at difficult models at 45°. But memorization difficulty did not interact with the motor effort for the look duration nor impact how people coordinated the eyes, head, and body to look at the models.

Consistent with previous studies [9, 8, 26, 85, 55, 59], we found that people adapt the motor-memory trade-off to different task conditions. That is, they looked more frequently when the eye-head-body movements were less effortful or when memorization was more difficult. In this study we extended the maximum target angle to 180° (the largest amplitude in the previous studies was 135° [9, 26]), which resulted in dramatically different eye-head-body coordination but had a modest effect on the motor-memory trade-off compared with 135°. Participants turned their eyes, head, and body very frequently to look at the models at 45°, but the frequency of eye-head-body movements to look at the model remained similar across 90°, 135°, and 180° angles. Yet, despite the stability of number of looks over this range, the mean duration of model looks did significantly increase from 90° until 180°. One possibility is that the eyes, head, and body need more time to change the state of rotational motion and stabilize the gaze for visual processing when making large gaze shifts. Alternatively, as the time of gaze shifts increased, participants may need longer to encode and rehearse the information in the memory to resist memory decay. These possibilities should be tested in future work.

Overall, memorization difficulty affected the number of looks and look duration but did not affect the motor-memory trade-off qualitatively. In other words, participants tended to move the eyes, head, and body frequently to look when the gaze shift amplitude was small regardless of the memorization difficulty, even though they could potentially use more memory to improve efficiency when the models were easier to memorize. It seemed that motor effort has a more pronounced effect on the motor-memory trade-off than memorization difficulty.

This is the first study to examine the eye-head-body coordination in the block-copying task. The current study demonstrated that each 45° increase in angle did not produce an equivalent change in effort. Although each segment (eyes, head, and body) increased in rotation as angles increased, the coordination among the eyes, head, and body at different angles were complex—the eyes contributed most to the gaze shifts when the amplitude was small; but even before the eyes reached the oculomotor limit, the head became increasingly involved; at larger angles, the body overtook the head in contributing the most for the largest gaze shifts.

How might the differential contribution of low-effort eye movements versus high-effort head/body movements relate to the motor-memory trade-off? Referring to Figure 2.4A and Figure 2.5A, the results showed that the big drop of the number of looks (between 45° and 90°) did not coincide with the sharp increase of the body rotation (between 135° and 180°). Instead, it co-occurred with the big increase in the head movement. In other words, the change in body movement did not affect the motor-memory trade-off much even though the body movement is more costly compared to head movement. Participants changed their strategy in copying the model by increasing the memory use once head movement was required to look at the models. This implies that the motor effort of eye movement is treated as distinct from the efforts of head and body movements by observers. Participants were more willing to move the eyes back and forth than moving both the head and the body probably because of the short time scale of saccadic eye movements (about 300 ms) [10]. But note that the current study only explored the eye-head-body movements underlying the motor-memory trade-off observed in a copying task. Future work should investigate how visual exploration relates to the effort of underlying effector movements across different tasks.

We acknowledge several limitations in our study. First, the unavailability of a full-body motion capture system made it impossible to track the rotations of trunk and feet. Body rotations were estimated by subtracting the eye and head rotations from the model angle. Although not ideal, this approximation could still shed light on the body movement in the copying task. Second, there were individual differences in how participants traded off between motor effort and use of memory. It was possible that individuals with higher memory capacity might choose to rely more on memory. Future studies could investigate the impact of memory capacity on the motor-memory trade-off. Last, we did not directly measure the energetic cost of the eye-head-body movements. A recent study showed that people did not spontaneously select the walking speed, step length and width that cost less energy while walking [5]. Likewise, we are unsure whether participants coordinated their eyes, head, and body in a way that was energetically optimal in the block-copying task.

In sum, this study enhanced our understanding of the motor-memory trade-off by investigating the underlying eye-head-body movements that guided looking in the block-copying task. We found that the eyes, head, and body coordinated differently when looking at different angles, resulting in varying motor effort. Future studies should further examine the interaction between the motor and cognitive systems.

Chapter 3

How Do People Change Motor-Memory Trade-Off Spontaneously with Practice?

3.1 Abstract

Previous studies have shown that people trade off between expending motor effort and using memory when completing a copying task that requires looking in different directions to gather information. For example, people tend to rely on memory less when making gaze shifts is less effortful (i.e. of small amplitude), but use memory more when the head and body movements are required to make large, effortful gaze shifts. However, it is unknown how people might change the motor-memory trade-off after repeated practice with the task. Would they choose a certain strategy and execute it more efficiently with

practice? Or would they discover a different strategy—using more memory rather than motor effort, over the course of practicing the task? To answer these questions, participants were asked to do a copying task repeatedly while wearing a mobile eye tracker and motion sensors. Participants' eye-head-body movements, and the frequency and duration of their visual exploration were recorded over the course of multiple trials. The results showed that participants increasingly used memory to reduce motor effort in the task, leading to improved efficiency.

3.2 Introduction

Suppose you received a code on your phone to login an account. Would you unlock your phone, open the message, and copy the code or would you memorize the code shown on the banner before it disappeared and then enter the code? This example illustrates the trade off between motor effort—opening the message to look at it–and use of memory. What you would do may depend on how effortful it is to open the message, for example, using face ID versus entering password on the screen, and how difficult it is to memorize the code accurately, for example, a 4-digit code versus a 10-digit code. Previous studies have showed that different task conditions, such as the cost of motor movements [9, 26, 55, 70], difficulty of memorization [93, 85, 59], time constraints [68], the cost of making errors [68, 106], the exposure to prior training [106] etc., affected the motor-memory trade-off. However, how people would change the trade-off over the course of practicing the task is unknown. What is the temporal change in people's decisions about whether to expend more motor effort or use memory over repeated performance of the same task?

People adjust their performance not only to different task conditions but also over the course of doing the task. For example, it has been well-documented in prior literature that participants improved performance spontaneously after repeated practice in a variety of perceptual-motor and cognitive tasks [31, 132, 73, 53, 4, 64, 112, 135, 15]. For example, novice participants improved performance in complex dance moves within an hour in a lab study [29]. Participants improved performance in different memory tests after practice [108, 79, 80, 119, 28]. Both short-term and long-term effects were observed—the improvement in performance after practice retained over short and long period of time [64, 108, 76]. However, the separate practice effects found in pure perceptual-motor tasks and pure cognitive tasks may not directly apply to the motor-memory trade-off, in which motor and cognitive systems dynamically interact with each other. How might people adjust the motor-memory trade-off with repeated practice? Do they improve task performance by executing the same strategy more efficiently? Or do they change the strategy, such as by more memory?

3.2.1 Trading Off Between Motor Effort and Memory

Previous studies have shown people tend to rely on motor effort in the motor-memory trade-off [9, 26, 93, 85]. Participants chose to move their eyes and head more frequently [9, 26, 93, 85], walk for longer distance [59], or carry boxes [38, 39, 37] rather than memorizing information. In our prior work, participants were asked to copy models positioned at different angles around them [93]. Their eye-head-body movements were recorded while copying the models. The results showed that participants moved their eyes, head, and body to look at the models frequently when the models were positioned at a small angle. They could improve the task efficiency by memorizing more information on the models to reduce the times of looking back and forth. But they did not do so. Although each model look was a low effort, by repeatedly looking to the model rather than memorizing, participants expended a high amount of unnecessary effort over the course of each trial.

One possible explanation for their inefficiency was that participants did not have enough practice to discover a more efficient way of completing the task. Would people change their motor-memory trade-off with repeated practice in the copying task? How might they change to improve efficiency? Do they improve by moving their eyes, head, and body more efficiently or using more memory? Those questions remained unknown.

Eye-Head-Body Coordination

Regarding the perceptual-motor performance, how might participants improve with repeated practice in the copying task? First, participants might improve the speed of moving their eyes, head, and body. Previous studies showed that participants decreased the latency of movements, moved faster, and had less errors in key-pressing, throwing, and kicking tasks [20, 19, 96, 21, 53]. It is possible that participants will rotate their eyes, head, and body more quickly in the copying task to improve efficiency with practice by making the same movements take less time.

Second, participants might change the eye-head-body coordination with repeated practice to make lower-cost movements do more of the total work. A prior study showed that participants restricted head movement at the beginning of a large-scale searching task but learned to coordinate the eyes and head later in the task [33]. It is possible that in the copying task participants might increase the proportion of eye and head movements to reduce costly body movements to improve efficiency. As a result, one aim of the current study was to record the movements of eyes, head, and body and investigate how they change with practice.

Strategy Change

In addition to the change in eye-head-body movements, participants might also improve cognitive performance with practice [57, 66, 107, 119, 28]. For instance, previous studies showed that participants responded faster and faster in recognizing and generating words in memory tests [108, 79, 80, 119, 28]. Participants made better decisions in a gambling game with practice [100]. Less time was required to solve arithmetic questions if participants were exposed to the similar questions before [89].

However, the findings about practice effects on strategy change are mixed. Some studies showed that participants stuck with their initial strategy, which could be inefficient, without adapting it to the changing task conditions over time. For example, in a prior study [90], participants were instructed to earn points by doing a visual search task. The quicker they achieved the goal points, the earlier they completed the task. Before each trial, participants were allowed to choose the difficulty level, which determined the points and penalty if making errors. The results showed that participants tended to make the same decision even though the task conditions subtly changed and they made more errors later. That is, their initial decision was no longer adaptive but they failed to monitor their performance. However, some other studies suggested the opposite. In a problem-solving task, without even receiving hints participants shifted to more efficient strategies after repeated trials [121]. Participants adopted a memory-based strategy in an associative learning task [82]. Children demonstrated strategy change as well in solving mathematical problems [89, 2].

Indeed, changing strategies come with a cost. Cognitive resources, such as memory, are limited, fragile, and expensive [98, 23, 61, 14]. There are limitations on the amount of information people could store and process in the memory [98, 23]. The information held in the memory may become inaccessible or inaccurate with time [61]. The overload of memory may impede other perceptual-motor or cognitive performance [14]. Also, changing strategies may be time-consuming and risky [90, 87, 121, 2]. Would people change their strategy—using more memory in the copying task? It is unclear because the cognitive system interacts with the motor system in the copying task. People could change the way they coordinate the eyes, head, and body to save effort so that they do not need to spend time exploring or changing different strategies. The change in strategies has to be efficient enough in saving effort to compete with the motor system given people predominantly tend to use more motor effort. Thus, the second aim of the current study was to determine whether people use more memory with practice over time.

3.3 Current Study

The current study focused on the practice effects on the motor-memory trade-off. Specifically, we investigated whether participants changed their eye-head-body coordination and/or copying strategy with repeated practice in the copying task [93]. Two research questions were asked:

1. Did participants change how they coordinated the eyes, head, and body over trials?

2. Did participants change their copying strategy to use more memory over trials?

To answer the first question, the movements of eyes, head, and body were recorded throughout the study. The absolute rotations of each segment (eye, head, and body) when participants looked at the models and the proportion each segment contributed to the gaze shifts were calculated to investigate the coordination among the three segments. Then we examined whether the rotations and corresponding proportions changed as participants did the copying task over repeated trials. We hypothesized that participants would adjust the eye-head-body coordination by increasing the proportion of relatively low-effort eye/head movements and decreasing the proportion of high-effort body movements. They would maximize the eye and head rotations to reduce body rotations when copying models at large angles.

To answer the second research question, we measured how many times participants looked at the model (i.e. *number of looks*) as an indicator of motor effort, and the mean duration each time participants looked at the model (i.e. *mean look duration*) as an indicator of memory use. We also calculated the total time participants spent in completing each trial (i.e. *trial duration*), and the proportion of time they spent looking at the models within a trial (i.e. *look proportion*) as measures of task efficiency. We examined how the motor-memory trade-off and task efficiency changed over trials. We hypothesized that participants would increasingly use more memory over trials to improve efficiency. Specifically, the number of looks should decrease while the mean look duration should increase; if so, the overall efficiency will increase as evidenced by decreases in trial duration (faster is better) and look proportion (spending less time looking at the model is better). Changes in efficiency should be greater for larger angles when the cost of movement is greatest.

The task, key apparatus, and procedure were the same as in [93]. But unlike the prior study [93] where the model for each trial was positioned at a random combination of angle and side, in the current study participants were assigned to only one of the angle conditions (i.e. 45°, 90°, 135°, 180°) and copied models of varying patterns at the assigned angle on the dominant-hand side for 16 trials. By doing so, we controlled the motor difficulty over trials and investigated if participants changed their eye-head-body coordination or motor-memory trade-off with practice.

3.4 Method

3.4.1 Participants and Design

Sixty-two college students were recruited from the introductory psychology class at the University of California, Riverside and received course credit for their participation in the study. The eye tracking videos of 11 participants were not recorded due to recording device failure. Another three participants were excluded due to poor pupil capture. The final sample for the eye tracking data analyses was 48 participants (17 males, 25 females, and 6 other, M age = 19.31 years, SD age = 1.50), 9 for the angle of 45°, 15 for 90°, 10 for 135°, and 14 for 180°. All participants had normal or corrected to normal vision and were not color blind. Forty-four participants were right-handed, three left-handed, and one ambidextrous. Participants described their ethnicity as Hispanic/Latinx (17) or not Hispanic/Latinx (24); seven participants chose not to answer. Participants described their race as Asian (16), White (10), American Indian/Alaska Native (8), More than One Race (2), and Other (4); eight chose not to answer.

Among the 48 participants, 11 participants were further excluded from the analyses of eye-head-body coordination based on the quality of the motion tracking data. Ten were due to the synchronization problems between eye tracking and motion tracking data; 1 was due to the malfunction of the motion sensors. As a result, the final sample for the motion tracking data analyses was 37 participants (15 males, 16 females, and 6 other, M age = 19.11 years, SD age = 1.43). Among them 9 copied models at the angle of 45°, 11 at 90°, 9 at 135°, and 8 at 180°.

This study used a mixed design. The between-subject factor was the angle at which the model was positioned. Participants were alternately assigned to one of the angles (45°, 90°, 135°, 180°) and copied the models positioned at the assigned angle on the dominant-hand side for 16 trials. The within-subject factor was trial number. We assessed the changes in the number of looks, look duration, and trial duration from trial to trial, and also measured the eye, head, and body rotation while participants looked at the models.

3.4.2 Apparatus

The experimental setup was the same as in [93] Figure 4.1. Participants stood in front of a music stand which held the *workspace*: an empty 4 × 4 grid with 8 magnets provided for participants to copy the model. The magnets were placed on the side of the grid corresponding to the participant's dominant hand. The *model* was displayed on another music stand which was positioned at the angle of 45°, 90°, 135°, or 180° to the left or right side of the participant. The distance from the participants to the workspace was

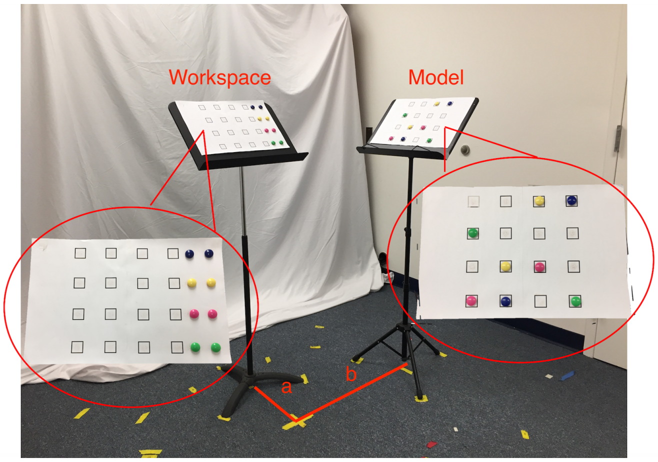


Figure 3.1: An example trial in which the model was positioned at 90° on the right side.

35.56 cm (the line ‘a’), and was 66.04 cm to the model (the line ‘b’). The height of the workspace and model were adjusted to the participant’s chest level. The model had a set of 16 different multi-colored patterns (4 colors, 2 magnets each color), which were generated by a computer script and used across all participants in the same order. Two wall-mounted security cameras (on the participants’ left and right sides) recorded the third-person view videos.

To capture eye movements, participants wore a Positive Science head-mounted eye tracker (Figure 3.2). The eye tracker has two cameras: a *scene camera* positioned over participants’ right eye recording the participants’ first-person field of view, and an *eye camera* that points to the participants’ right eye and records the eye movements. The two cameras are mounted on a lightweight eyeglass frame. The videos recorded by the two cameras (sampling rate 30 Hz) were streamed to a recording device attached to the shoulder band worn by participants.

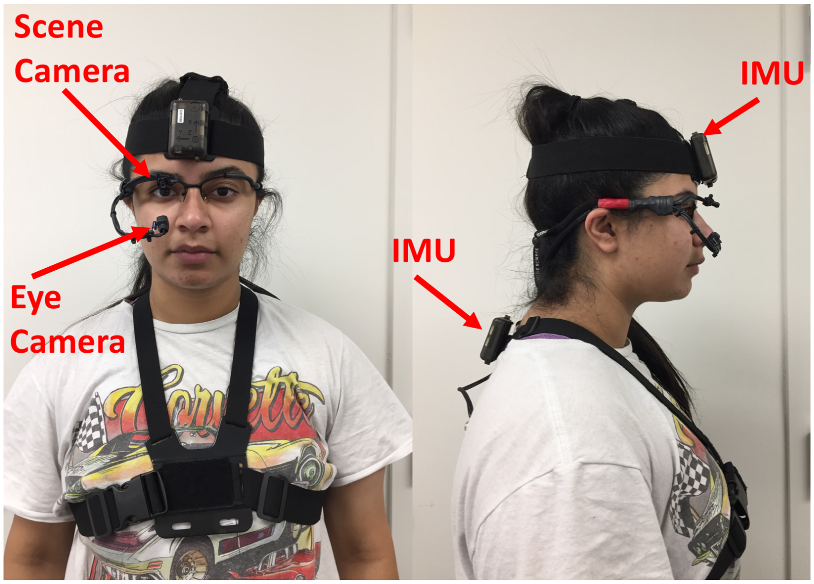


Figure 3.2: Participants wore a head-mounted eye tracker, which has an eye camera and a scene camera, and two IMUs placed at the forehead and the base of neck were attached to a headband and a shoulder band.

To capture head movements, participants wore two wireless STT Systems IWS inertial measurement units (IMUs) (dimensions: 56 × 38 × 18 mm, 46 g): one on the forehead (attached to a head band), the other on the neck (attached to a shoulder band) at the C7 vertebrae (Figure 3.2). The IMUs streamed acceleration and gyroscope data at a rate of 400 Hz over WiFi to the STT software installed on a laptop, which recorded the data.

3.4.3 Procedure

The procedure was similar to [93]. In the 1-hour long session, participants were instructed to complete the model-copying task, before and after which they completed brief calibration for the eye tracker and IMUs.

Calibration and Synchronization for the Eye Tracker and IMUs

After giving consent, participants put on a shoulder band, a head band, and the eye tracker. The experimenter adjusted the cameras of the eye tracker to ensure the scene camera would capture the participant's first-person field of view and the eye camera would capture the pupil and corneal reflection no matter how participants moved their eyes. The experimenter attached the IMUs to the headband and shoulder band worn by the participants and ensured they were at the correct positions and orientation.

To calibrate the eye tracker, participants stood 35 cm away from a cardboard poster (76 cm × 51 cm), which was put on the music stand. Nine targets (2.5 × 2.5 cm) were drawn on the board: 4 at the corners, 4 at the midpoints of each edge, and 1 at the center. Participants were asked to move their eyes to look at specific targets while keeping their head still. The eye tracker measured the rotations of eyes while participants were looking at different targets in the field of view and determined the gaze direction in pixels relative to the scene camera video. The same calibration procedure was repeated in the middle and end of the model-copying task to ensure the accuracy of eye tracking throughout the session.

To calibrate the IMUs and to synchronize with the eye tracking data for subsequent analyses, participants were asked to look forward, keep the chin parallel to the floor and still for a while, and then quickly turn the head to the left and right. These motions created identifiable moments in the IMU data to be synchronized with the eye tracking data. The experimenter checked the visualization of the IMUs data on the software to ensure it showed the correct motions.

Model-Copying Task

Participants completed two practice trials and 16 experimental trials of the model-copying task. A set of 16 different configurations of the model patterns were randomly created by a computer script and used across participants. The model was positioned on the side of the participant's dominant hand at the assigned angle (45°, 90°, 135°, or 180°). In each trial, participants were required to copy the model correctly while standing at a designated spot on the floor (the wrongly copied trials were excluded from the data analyses). They were also required to pick up one magnet at one time with the dominant hand. They faced toward the workspace at the beginning of each trial but were allowed to freely turn their head, body, and feet to look at the model as many times as they needed while copying the model. They were reminded to close their eyes while the experimenters changed the model between trials.

3.4.4 Data Processing and Analyses

Synchronizing the data collected from the eye tracker and IMUs was conducted as in [93].

First, the eye rotation in each frame of the scene videos (in unit of pixels) was calculated from the eye and scene videos recorded by the eye tracker using the software Yarbus (Positive Science). The time series of horizontal eye rotation in pixels were then converted to degrees based on the camera's horizontal field of view and lens correction, as in [45].

Second, the acceleration and gyroscope data recorded by the IMUs were used to calculate the time series of horizontal head rotation in degrees relative to the base of the neck by the software iSen (STT Systems).

Third, to synchronize the eye tracking and IMU data, the experimenter identified the sharp head turns participants made during calibration in the time series of IMU data and the corresponding moments in the scene videos (quick shifts of field of view). The experimenter marked down the times of the head turns and the frame numbers in the videos and then converted the times series to the unit of frames in a Matlab script.

After synchronization, for each frame of the trials in the scene videos, two independent coders tagged each instance of gazing at the model. If the participants' eye gaze fell within the area of model in the field of view for at least 2 frames (allowing 1 frame off or a blink in between), a *model look* was defined. The inter-rater reliability was high (97.69% agreement).

To answer the research questions, two sets of analyses were conducted. First, for the eye-head-body coordination data, two 3-way linear mixed-effect models (LMMs) predicting the rotation (in degree) and proportion (%) separately were calculated with angle (4 levels, 45°, 90°, 135°, 180°), trial (linear variable from 1 to 16), and segment (3 levels, eye, head, body) as the independent variables. The participant was included as a random effect in the LMMs. For example, the model used to test the effects on the rotation was: rotation $\sim$ angle $\times$ trial $\times$ segment + (1 — participant).

Second, for the question of strategy change over trials, four 2-way LMMs were applied to test the effects of angle and trial on four dependent measures (i.e., number of looks, look duration, trial duration, look proportion) separately. Angle and trial were included as fixed effects, and participant was included as a random effect. For example, the model used to test the effects on the number of looks was: number of looks ~ angle × trial + (1 — participant). The *lme4* [11] package in R [110] was used to calculate all LMMs. ANOVAs were used to test significance of main effects and interactions from the LMMs using the *lmerTest* package in R [83]. Degrees of freedom were determined by the Satterthwaite approximation [117, 92]. Follow-up pairwise comparisons used the Holm-Bonferroni correction to adjust for multiple comparisons.

3.5 Results

Two sets of results investigated the changes in eye-head-body coordination and the motor-memory trade-off over trials across angles.

3.5.1 Eye-Head-Body Coordination

First, to examine if participants changed their eye-head-body coordination over trials, we calculated the mean rotation of eye, head, and body during each model look, and the proportion each segment contributed to make gaze shifts for each trial.

The descriptive statistics are shown in Table 3.1. Regarding the change over trials, eye rotations did not change over trials in any of the angle conditions; head rotation increased over trials at the 45° angle condition but remained the same for the other angles; body rotation decreased over trials at 45° and remained similar for the other angles. The results for the corresponding proportions showed the same trends (Figure 3.3). This implied

Table 3.1: Descriptive statistics (*M* and *SD*) for the rotation (in degree) and proportion by angle and segment. Note that the proportions were calculated at the trial level, so the sum of mean proportions is not equal to one.

	Rotation			**Proportion**		
	Eye	Head	Body	Eye	Head	Body
45°	20.30(4.34)	10.02(7.44)	14.99(9.45)	.45(.10)	.22(.17)	.33(.21)
90°	31.01(6.36)	27.58(9.68)	31.41(11.12)	.34(.07)	.31(.11)	.35(.12)
135°	32.44(7.45)	44.88(13.90)	57.68(17.85)	.24(.06)	.33(.10)	.43(.13)
180°	31.89(8.42)	59.30(16.61)	89.10(18.37)	.18(.05)	.33(.09)	.50(.10)

that with repeated practice completing the task, participants adjusted the eye-head-body coordination only in the small angle condition. They increased the head rotation to reduce the body rotation, leading to decreased motor effort overall. However, they had less flexibility in adjusting the eye-head-body coordination at large angles as they had to rely on the body rotation to make gaze shifts, likely explaining why no change was observed.

Regarding the differences in coordination between angle conditions, results replicated [93] that the eye-head-body coordination differed as larger angles required larger shifts of gaze. As Figure 3.4A shows, the eye, head, and body rotations all increased as the angle of the models increased, but each segment (eye, head, or body) increased at different rates. The body rotation increased most; the head rotation increased moderately; the eye rotation increased from $45^{\underline{o}}$ to $90^{\underline{o}}$ and then remained almost the same across the larger angles. Proportionally, the contribution of eye movement to the gaze shifts decreased as the angle increased (Figure 3.4B). The contribution of head movement first increased and then remained stable. The contribution of body movement increased continuously. This implied that participants mainly moved the eyes to look at the models at small angles. When larger

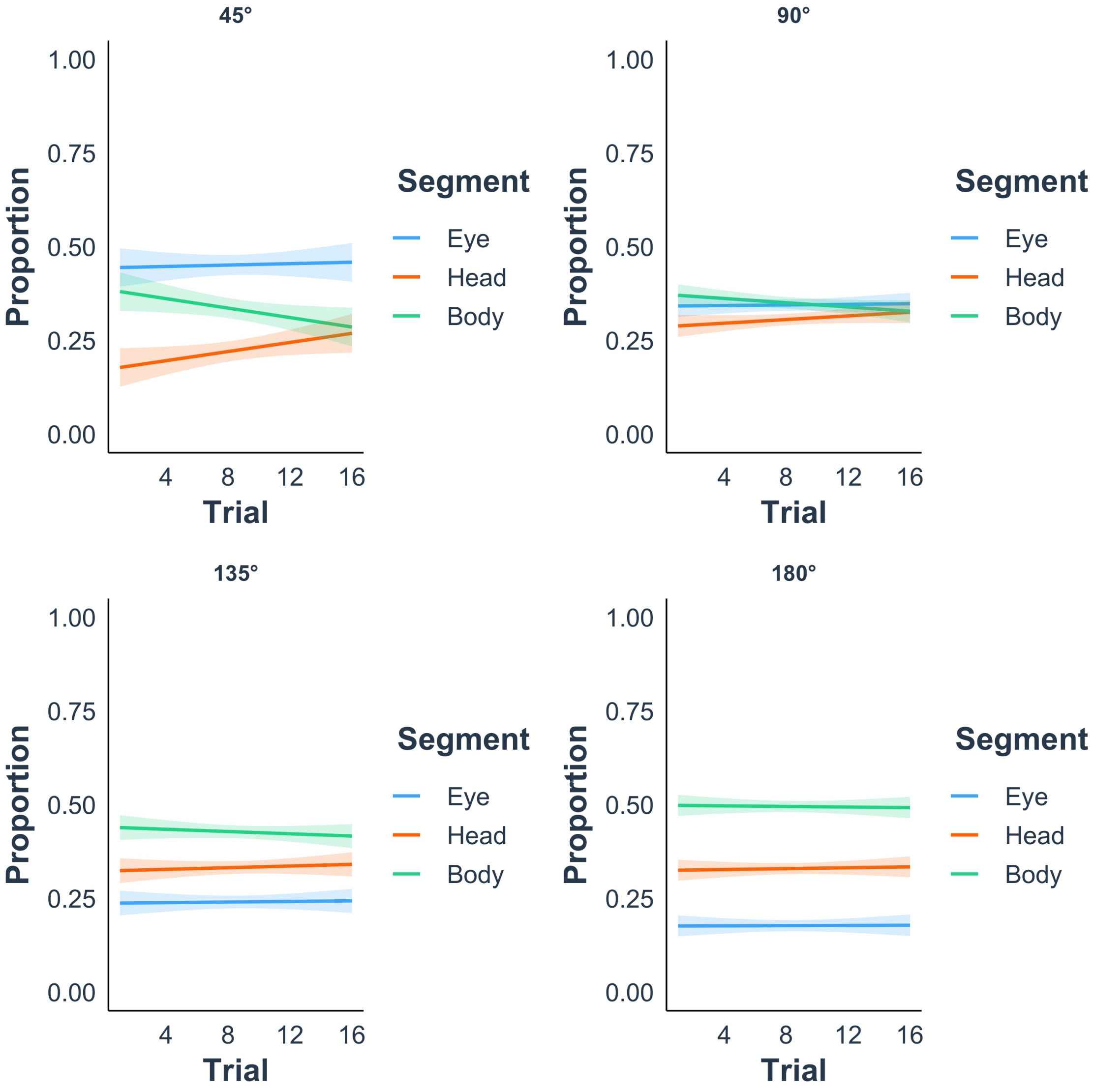


Figure 3.3: Summaries of model predictions for the eye, head, and body proportions (separate colored lines) over trials (x-axis) for different angles.

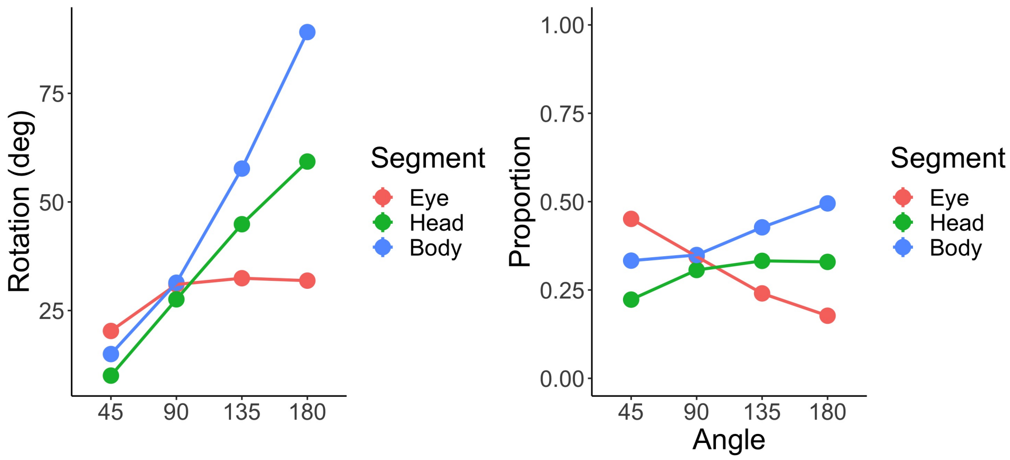


Figure 3.4: A: The average eye, head, and body rotations at different angles. B: The proportion that the eye, head, and body movements contributed to the gaze shifts as the angle increased. Note that the proportions were calculated at the trial level, so the sum of mean proportions is not equal to one.

movements were required to look at the models, the participants then relied more on head and body movements.

The results of the LMMs (Table 3.2) predicting the rotation showed main effects of angle (4 levels: 45°, 90°, 135°, 180°) and segment (3 levels: eye, head, body), an interaction between angle and segment, and an interaction between trial and segment. To follow up on the angle × segment interaction (Table 3.3), pairwise comparisons showed: at 45°, the eye ($t(1696) = 7.503$, $p < .001$) and body ($t(1696) = 3.609$, $p < .001$) rotations were greater than the head rotation, and the eye rotation was greater than the body rotation ($t(1696) = 3.894$, $p < .001$); at 90° the eye ($t(1696) = 2.764$, $p = .012$) and body ($t(1696) = 3.078$, $p = .006$) rotations were greater than the head rotation, but no difference between the eye and body rotation ($t(1696) = .314$, $p = .754$); at 135° the eye rotation was smaller than the head ($t(1696) = -9.003$, $p < .001$) and body rotations ($t(1696) = -18.323$, $p < .001$),

Table 3.2: Summary of LMM results predicting rotation and proportion from angle, trial, and segment.

		Rotation			**Proportion**		
	df	*F*	*p*		*F*	*p*	
Angle	3	259.71	<.001	***	.00	1.000	n.s.
Trial	1	.02	.902	n.s.	.02	.889	n.s.
Segment	2	121.08	<.001	***	60.41	<.001	***
Angle × Trial	3	.01	.999	n.s.	.01	.999	n.s.
Angle × Segment	6	45.88	<.001	***	25.60	<.001	***
Trial × Segment	2	3.52	.030	*	6.34	.002	**
Angle × Trial × Segment	6	.15	.989	n.s.	1.35	.230	n.s.

$^*p<.05$, $^{**}p<.01$, $^{***}p<.001$

Table 3.3: Pairwise comparisons between segments for each angle.

	Rotation
45°	Eye > Body > Head
90°	Eye = Body > Head
135°	Eye < Head < Body
180°	Eye < Head < Body

and the head rotation was smaller than the body rotation ($t(1696)$ = -9.320, $p < .001$); at 180° the eye rotation was smaller than the head ($t(1696)$ = -18.790, $p < .001$) and body rotations ($t(1696)$ = -38.898, $p < .001$), and the head rotation was smaller than the body rotation ($t(1696)$ = -20.420, $p < .001$).

To follow up on the trial × segment interaction, a LMM predicting the rotation from trial and segment was conducted separately for different angles. As Table 3.4) shows, for the angle of 45°, the results of LMM showed the main effect of segment and the interaction between trial and segment. To follow up on the trial × segment interaction, the linear trend estimates showed similarity in the eye rotation over trials, an increase in the head rotation, and a decrease in the body rotation. However, the results of LMMs only showed

Table 3.4: Summary of LMM results predicting rotation from trial and segment for different angles.

		45°			**90°**		
	df	*F*	*p*		*F*	*p*	
Trial	1	.02	.891	n.s.	.00	1.000	n.s.
Segment	2	25.17	<.001	***	7.31	<.001	***
Trial × Segment	2	4.38	.013	*	2.46	.086	n.s.

$^{*}p<.05$, $^{**}p<.01$, $^{***}p<.001$

		135°			**180°**		
	df	*F*	*p*		*F*	*p*	
Trial	1	.00	1.000	n.s.	.01	.909	n.s.
Segment	2	30.67	<.001	***	105.63	<.001	***
Trial × Segment	2	.51	.599	n.s.	.09	.910	n.s.

$^{*}p<.05$, $^{**}p<.01$, $^{***}p<.001$

the main effect of segment without interaction for 90°, 135°, and 180°: the eye, head, and body rotations remained similar over trials.

The results of the LMMs (Table 3.2) predicting the proportion showed the main effect of segment, an interaction between angle and segment, and an interaction between trial and segment. To follow up the angle × segment interaction (Table 3.5), pairwise comparisons showed that: the proportion that the eyes contributed to the gaze shifts decreased significantly from 45° to 90° ($t(272) = 8.082$, $p < .001$), from 90° to 135° ($t(275) = 7.870$, $p < .001$), and from 135° to 180° ($t(280) = 4.376$, $p < .001$); the proportion of head rotation increased from 45° to 90° ($t(272) = -6.334$, $p < .001$), remained no change from 90° to 135° ($t(275) = -1.939$, $p = .107$), and from 135° to 180° ($t(280) = .195$, $p = .845$); the proportion of body rotation was similar between 45° and 90° ($t(272) = -1.222$, $p = .223$), but increased from 90° to 135° ($t(275) = -5.931$, $p < .001$), and from 135° to 180° ($t(280) = -4.680$, $p < .001$).

Table 3.5: Pairwise comparisons between adjacent angles for each segment based on the proportion of each gaze shift.

	Proportion
Eye	$45° > 90° > 135° > 180°$
Head	$45° < 90° = 135° = 180°$
Body	$45° = 90° < 135° < 180°$

To follow up on the trial × segment interaction, a LMM predicting the proportion from trial and segment was conducted separately for different angles. As Table 3.4) shows, for the angle of 45°, the results of LMM showed the main effect of segment and the interaction between trial and segment. To follow up on the trial × segment interaction, the linear trend estimates showed no change in the eye proportion over trials, an increase in the head proportion, and a decrease in the body proportion. However, the results of LMMs only showed the main effect of segment without interaction for 90°, 135°, and 180°. The eye, head, and body proportions all remained similar over trials.

3.5.2 Motor-Memory Trade-Off

Second, to examine if participants changed the copying strategy over trials, 4 dependent variables were calculated for each trial:

1. *Number of looks*: the total number of model looks in a trial. The larger the number of looks is, the more frequently the participants moved their eyes, head, and body to look at the models (expending greater effort). The hypothesized decreasing number of looks over trials suggested less motor effort expended by participants.

2. *Look duration*: the duration of an average model look in a trial. This variable was calculated by calculating the mean duration of all model looks in a trial (in unit

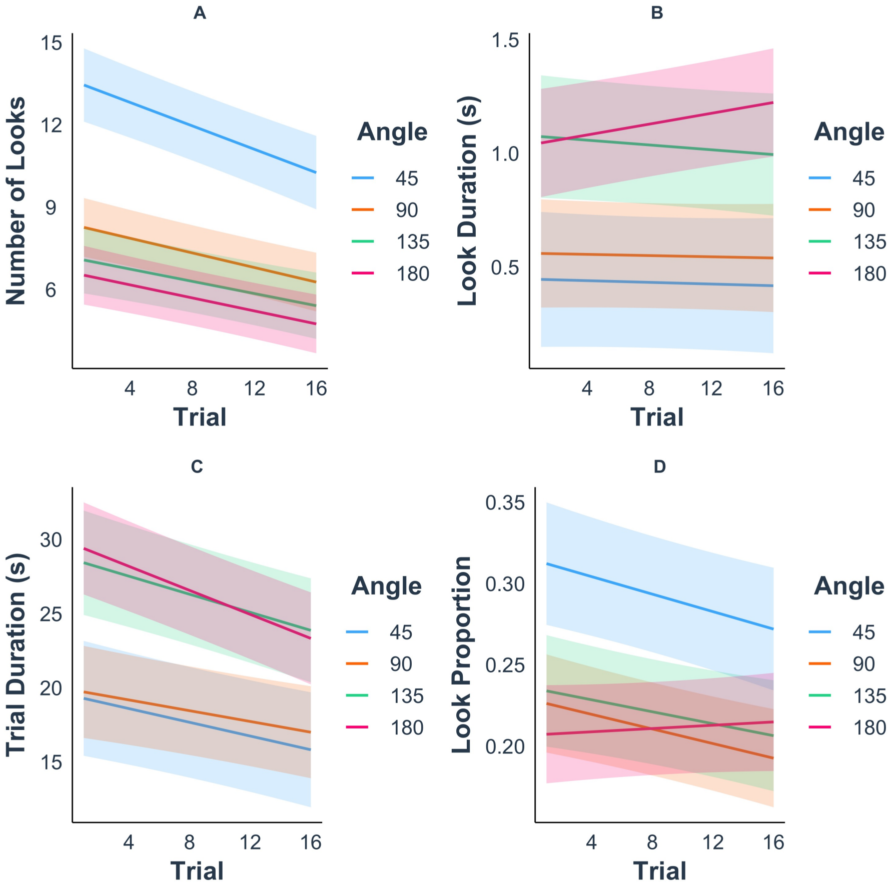
of frames then converted to seconds). Longer average look durations suggest that participants spent longer in memorizing the models. The hypothesized increasing look duration over trials suggested more memory use by participants

3. *Trial duration*: the total time spent in completing each trial. The shorter trial duration indicated higher task efficiency. Trial duration was hypothesized to decrease over trials as participants practiced.

4. *Look proportion*: the proportion of time spent looking at the models within a trial. This variable was calculated by dividing the total look time by trial duration (note the total look time was calculated by multiplying number of looks and look duration). The higher look proportion indicated participants proportionally spent longer looking at the models.

Results demonstrated the effect of practice: over trials participants moved their eyes, head, and body less frequently to look at the model but the mean look duration remained the same across angles. Participants used less and less time to complete each trial (Figure 3.5C) while continuing to perform the task accurately, indicating increased efficiency. Although the look proportion decreased for all angles (Figure 3.5D), participants spent significantly more time looking at the model proportionally when less motor effort was required to make the gaze shifts. Regarding the differences across angles, results replicated [93] that participants looked more frequently with shorter duration at the models positioned at a small angle (requiring less motor effort) compared to larger angles (requiring greater

Figure 3.5: Summaries of model predictions for (A)the number of looks, (B) mean look duration, (C) trial duration, and (D) look proportion over trials (x-axis) across angle (separate colored lines).



motor effort) (Figure 3.5A and B). This implied that participants expended more motor effort when the movements of making gaze shifts were less effortful.

The results of the LMM predicting the number of looks showed significant main effects of angle and trial (Table 3.6). Participants looked at the models less frequently when the models were at larger angles. Follow up pairwise comparisons showed a greater number of looks for 45° ($M = 11.89$, $SD = 2.98$) compared to 90° ($M = 7.28$, $SD = 2.42$), 135° (M

Table 3.6: Summary of LMM results predicting the number of looks, look duration, trial duration, and look proportion from angle and trial.

		Number of Looks			**Look Duration**		
	df	*F*	*p*		*F*	*p*	
Angle	3	23.82	<.001	***	5.62	.002	**
Trial	1	113.53	<.001	***	.15	.699	n.s.
Angle × Trial	3	2.54	.056	n.s.	3.29	.020	*

**p*<.05, ***p*<.01, ****p*<.001

		Trial Duration			**Look Proportion**		
	df	*F*	*p*		*F*	*p*	
Angle	3	10.32	<.001	***	6.65	<.001	***
Trial	1	78.67	<.001	***	18.25	<.001	***
Angle × Trial	3	2.81	.039	*	4.25	.006	**

**p*<.05, ***p*<.01, ****p*<.001

Table 3.7: Pairwise comparisons between adjacent angles for the number of looks, look duration, trial duration, and look proportion.

Number of looks	$45° > 90° = 135° = 180°$
Look duration	$45° = 90° < 135° = 180°$
Trial duration	$45° = 90° < 135° = 180°$
Look Proportion	$45° > 90° = 135° = 180°$

= 6.27, *SD* = 2.53), and 180° (*M* = 5.63, *SD* = 2.34) (Table 3.7). There was no difference between 90°, 135°, and 180°. For all angles, the number of looks decreased over trials.

The results of the LMM predicting mean look duration showed a significant main effect of angle and the interaction between angle and trial (Table 3.6). Follow up pairwise comparisons on the main effect of angle showed that the look duration was significantly shorter at 45° (*M* = .43, *SD* = .10) and 90° (*M* = .55, *SD* = .31) compared to 135° (*M* = 1.03, *SD* = .53) and 180° (*M* = 1.13, *SD* = .73) (Table: 3.7). No difference was found between 45° and 90° or between 135° and 180°. Follow up pairwise comparisons on the angle × trial interaction showed that the look duration slightly increased over trials at 180° but remained similar at other angles.

The results of the LMM predicting trial duration showed significant main effects of angle and trial, and the interaction between angle and trial (Table 3.6). Follow up pairwise comparisons on the main effect of angle showed that the trial duration was shorter at 45° (M = 5.13, SD = 1.62) and 90° (M = 3.94, SD = 2.05) compared to 135° (M = 5.81, SD = 2.49) and 180° (M = 5.65, SD = 3.01) (Table 3.7). No difference between 45° and 90° or between 135° and 180°. Over trials, participants used less time to complete each trial but to different extents across angles. The decrease rate for 90° was significantly smaller than 180° (p = .028).

The results of the LMM predicting mean look proportion showed significant main effects of angle and trial, and the interaction between angle and trial (Table 3.6). Follow up pairwise comparisons on the main effect of angle showed that the look proportion was greater at 45° (M = .29, SD = .07) than 90° (M = .21, SD = .07), 135° (M = .22, SD = .06) and 180° (M = .21, SD = .07) (Table 3.7). No difference was found between other angles. Follow up pairwise comparisons on the angle × trial interaction showed that over trials, the look proportion decreased for 45°, 90°, and 135° but did not change for 180°.

3.6 Discussion

The current study investigated how participants coordinated the eyes, head, and body and traded off motor effort and memory use with repeated practice in the copying task. We hypothesized that participants could become more efficient by improving their eye-head-body coordination and/or by changing their strategy, and found evidence of both types of improvement over the course of trials. Regarding the changes in the eye-head-body coordination, participants increased their head rotation and decreased their body rotation in the 45º condition that involved smaller shifts of gaze, reducing motor effort. However, when body movements were required to make larger gaze shifts in the larger angle conditions, the eye-head-body coordination remained similar over trials. In terms of the changes in the motor-memory trade-off, participants used more memory over repeated trials to improve task performance. This indicated strategy change during repeated practice. Specifically, participants looked less frequently at the models over trials, spent less time in inspecting the models totally, and completed the copying task faster in each trial.

3.6.1 Eye-Head-Body Coordination at Different Angles Over Trials

A highlight of the study was to capture the eye-head-body coordination at different angles over repeated trials. Consistent with previous studies [93, 47, 67, 45, 109, 120], the results showed that the eyes, head, and body coordinated in different ways when making gaze shifts of different amplitudes. The eye movements contributed more when the models were positioned at a small angle, whereas the head and body movements contributed more at the larger angles. With repeated practice, participants increased the head proportion to lower the body proportion when making small gaze shifts.

Indeed, the motor effort to look depends on how the eyes, head, and body are coordinated to shift gaze [43, 42, 86, 123, 45, 48, 120]. First, the eyes, head, and body movements have different biomechanical properties. Eye movements are quick with smaller range of rotation whereas the head and body movements are slow with larger range of rotation [86, 67, 60, 123, 3, 126, 51]. Second, eye movements cost less energetically compared to head and body movements [122]. Thus, people might trade off between the eye movements and use of memory differently compared to the head and body movements.

It is noted that participants gradually increased the proportion of head movements rather than the lower-effort eye movement to reduce body movement when making small gaze shifts. However, based on previous research [58, 126], the oculomotor range of human eyes is ±55° horizontally. That is, participants could theoretically rotate the eyes to a larger degree to reduce the head or body movements. But they did not do so in the task. It may imply compared to the head, people tend to keep the eyes centered [16, 45].

3.6.2 Changes in the Copying Strategy

Another highlight of the study was to examine the changes in the motor-memory trade-off over repeated trials. Using a between-subject design, the current study duplicated the prior work [93] that participants tended to use more memory if making gaze shifts was too effortful. When the models were positioned at a small angle, participants looked more frequently with shorter duration at the models. However, they reduced the frequency of model looks and looked longer each time when the models were positioned at large angles.

Moreover, the results suggested that participants used more memory with practice. Over repeated trials, participants decreased the times of looking at the models regardless of angles. They improved memorization efficiency as the mean look duration remained similar (at least for 45, 90, and 135) but they remembered more information each time they looked at the models. In total, participants spent less time inspecting the models and completing the task, implying higher efficiency in performing the copying task.

Nevertheless, the results indicated that after repeated practice participants were still inclined to expend more motor effort rather than using memory if making gaze shifts was less effortful. The number of looks did not drop below the number of items on the models for the small angle. That is, participants still unnecessarily looked at the closer models very frequently in the last few trials. However, participants were willing to use more memory over trials if the models were positioned at large angles. This implied that different movements—the low-effort eye movements versus high-effort head and body movements, might be carefully evaluated in the motor-memory trade-off by participants. The eye movements are easy and quick so that people choose to use them more rather than memory. In contrast, the head and body movements are effortful. People then choose to use more memory.

3.6.3 Practice Effects on Motor-Memory Trade-Off

Consistent with previous studies, this study showed that participants improved the motor and cognitive efficiency with repeated practice in the copying task. Physically, participants looked less frequently at the models. In addition to reducing the number of model looks, participants also spontaneously changed the way they coordinated their eyes, head, and body to decrease motor cost. Cognitively, participants used more memory.

Combining the two sets of results, it can be seen that the motor-memory trade-off is a dynamic process that evolves over time. People trade off between motor effort and use of memory when first encountered the task. Different task characteristics have an impact on the trade-off [9, 26, 55, 70, 93, 85, 59, 68, 106]. With practice, the efforts of eye-head-body movements and memorization both decrease, leading to different trade-off. In general, employing cognitive resources, such as the use of memory, is a more efficient strategy to improve performance, but memory use becomes more difficult when approaching the limits of memory capacity. People continuously adjust strategies within and between systems, and trade off accordingly.

Results also highlighted that some changes due to practice in the eye-head-body coordination and motor-memory trade-off were universal across angles, whereas others were angle specific. For example, participants looked at the model less frequently after repeated practice regardless of angle. However, participants optimized the eye-head-body coordination to decrease the total motor cost at a small angle but not at a large angle. They spent slightly longer looking at the models to memorize the information at a large angle but not at a small angle. The findings suggested that people become optimal within the constraints of the task.

Lastly, we acknowledged that this study only examined the spontaneous changes in the motor-memory trade-off with repeated practice. Participants still looked at the models more often than was necessary—which was inefficient, in the small angle condition after multiple trials of spontaneous practice. It is unknown how people might further improve efficiency if given instructions or feedback [105, 131, 129, 52]. Future studies should look at how people change the motor-memory trade-off after exploring more efficient strategies.

3.6.4 Conclusion

To sum up, the current study investigated the practice effects on the motor-memory trade-off. The findings showed that participants improved task performance by expending less motor effort and used more memory with repeated practice. Specifically, they looked less frequently at the models and increased the proportion of head rotation to make small gaze shifts. They also memorized more information efficiently. Future studies will examine if forcing people to learn a more efficient strategy further improves the task performance.

Chapter 4

Does Inducing People to Test a Different Strategy Lead to Later Adoption of a More Efficient Strategy?

4.1 Abstract

Previous studies have shown that people trade off between expending motor effort and using memory when copying information, and adjust the trade-off spontaneously over the course of repeated practice. However, it is unknown whether manipulating motor effort might lead to participants discovering a more efficient strategy. Thus, the current study restricted people's head movements and tested if the increased motor cost due to head

restriction would lead people to discover a more efficient strategy that depends on memory. We compared the eye-head-body coordination and copying strategy (i.e. expending more motor effort or using memory) before, during, and after the head restriction. Participants wore a neck brace during the head-restriction block of trials to increase the motor effort of looking. Using motion sensors and a mobile eye tracker, we recorded participants' eye-head-body movements and identified when they looked at the models. The results showed that participants increased eye and body movements to compensate for the head restriction, but returned to their original eye-head-body coordination after head restriction was removed. In terms of the copying strategy, participants increased the use of memory with head restriction and continued using the memory-based strategy to improve task efficiency after removing the restriction. The findings implied that restriction may lead people to discover and adopt a more efficient strategy.

4.2 Introduction

People trade off between expending motor effort and using memory when gathering information [9, 26, 55, 70, 93]. For example, in our prior work [93], participants were instructed to copy models positioned at different angles around them. To gather visual information about the model, participants might choose to look frequently at the model (i.e. expending more motor effort) or hold more information in memory to reduce frequent model looking. Participants looked more frequently at the model when it was positioned at a small angle (requiring less motor effort) but used more memory to reduce model looking when the models were at larger angles (requiring more motor effort). Despite this trade-off between conditions, participants did not maximize their efficiency in any condition—they consistently looked more times than was necessary.

How might people improve their efficiency when trading off between memory and motor effort? Repeated experiences with the same task might allow people to spontaneously discover more efficiency strategies [94]. In the study, participants copied the models positioned at one assigned angle for multiple trials and we recorded how their eye-head-body coordination and copying strategy changed over the course of repeated practice. Results showed that participants looked less frequently and used more memory after repeated practice with the task. They completed the copying task more and more quickly over trials, indicating an improved efficiency. Also, we found that participants changed the way in which the eyes, head, and body coordinated to make gaze shifts of small amplitude with repeated practice. Specifically, to gather the information on the model at a small angle, participants gradually increased the head movement to reduce the body movement to lower the total motor cost.

However, participants' performance was sub-optimal after repeated practice [94]. They still relied on frequent model looking rather than memorization to gather the information. For instance, in the 45° condition, participants on average looked at the model 11 times at the end of multiple trials, which exceeded the total number of items on the model (i.e. 8) [94]. Optimally, if participants memorize the positions of 1 or 2 items per model look, they could complete the copying in 8 or 4 looks, which is way lower than 11. In the current study, we further investigated whether increasing the motor effort of looking might lead to the discovery and later adoption of a more efficient memory use strategy.

4.2.1 Strategy Exploration

Some previous studies showed that people do not always settle on efficient information-gathering strategies when allowed to spontaneously choose how to perform a task [84, 46]. In one of the studies [84], participants were asked to wear a backpack and make judgments about whether they could squeeze through doorways of different widths. Participants failed to make accurate judgments even though they were allowed to explore the doorway in any way they thought would be helpful. Perception was only recalibrated successfully after participants were explicitly instructed to try squeezing through the doorway to practice. That is, participants did not spontaneously discover the most efficient strategy (in this case practicing squeezing through the doorway) and detect the useful information. In addition, the failure was not due to low motivation because the group who received monetary rewards for better performance was no more likely to discover an efficient strategy compared with a no-reward group.

Furthermore, some studies provided evidence that participants were capable of using more efficient strategies but did not do so without training or prompts [105, 131, 129]. In one example [129], participants were asked to determine if the target pair of nouns matched one of the pairs in a table shown on the same screen. Results showed that even after trials of practice, participants still tended to look up the table to verify if the pairs matched, instead of memorizing the table and then comparing the target to the memory to improve efficiency. As comparison, participants in another group went through some trials (randomly inserted into the regular trials) in which they were asked to recognize if the target matched without displaying the table. Those trials were used for the purpose of prompting increased use of memory and removed from the data analyses. Results showed that this group of participants were more likely to memorize the table and the response time decreased significantly. It implied that participants were able to use a more efficient strategy for higher efficiency but they did not choose to do so spontaneously.

Exposing people to different strategies might lead them to later adopt more efficient strategies. Howes and colleagues [68] asked participants to copy appointment information from an email application to a calendar on a computer. Participants went through two phases—the no-choice and choice phases. In the no-choice phase, participants were required to memorize certain numbers of appointments (from 3 to 9) at a time and then copy them to the calendar. Afterwards, participants went through the choice phase in which they could decide how many appointments to remember each time opening the email. Results showed that the number of appointments participants chose to remember in the choice phase was the one producing highest copying correct rate in the no-choice phase. The results implied that participants learned the most efficient way to do the task after trying all possible strategies.

4.3 Current Study

Prior work showed that even after repeated practice for trials, participants do not settle on an efficient motor-memory trade-off strategy [94]. Exposing participants to unfamiliar strategies may help them spontaneously adopt a more efficient one. Thus, in the current study, we manipulated the motor effort of eye-head-body movements to investigate if the varied eye-head-body coordination induces strategy changes. Specifically, we restricted participants' head movements in the copying task [94], and compared participants' eye-head-body movements and copying strategies before, during, and after the head restriction. By doing so, we attempted to answer two research questions. First, how did participants coordinate the eyes, head, and body with head restriction and after removing the head restriction? Second, how did participants change their copying strategy with head restriction and after removing the head restriction?

Participants completed 3 consecutive blocks of 10 trials—pre-restriction, restriction, and post-restriction. In the pre- and post-restriction blocks, participants copied the models without any head restriction as in the prior work [94]. In the restriction block, participants wore a neck brace while copying the models to make head movements more difficult. Note that participants repeatedly copied models positioned at one angle—either 45° or 135° in the current study. We chose those two angles because the prior work showed that participants' performance at 45° was distinct from at larger angles (i.e. 90°, 135°, 180°) but there was little difference across the large angles [93, 94].

To answer the first question on eye-head-body coordination, we recorded participants' eye-head-body movements throughout the study. To compare between the angle conditions, we calculated the proportion that each segment (i.e. eye, head, and body) contributed to the gaze shifts when participants looked at the models. Then we compared the mean proportions between the blocks. We hypothesized that participants would increase the proportions of the eyes and body to compensate for the restricted head movements, but resume the eye-head-body coordination after removing the head restriction. The way they coordinated the eyes and body to compensate for the head restriction may be different for different angles.

To answer the second question on the copying strategy, we calculated 4 dependent variables and compared them between the blocks.

1. *Number of looks*: the total number of model looks in a trial. The larger the number of looks is, the more frequently the participants moved their eyes, head, and body to look at the models (expending greater effort).

2. *Look duration*: the duration of an average model look in a trial. This variable was calculated by calculating the mean duration of all model looks in a trial (in unit of frames then converted to seconds). Longer average look durations suggest that participants spent longer memorizing the models.

3. *Trial duration*: the total time spent in completing each trial. The shorter trial duration indicated higher task efficiency.

4. *Look proportion*: the proportion of time spent looking at the models within a trial. This variable was calculated by dividing the total look time by trial duration (note the total look time was calculated by multiplying number of looks and look duration). The higher look proportion indicated participants proportionally spent longer looking at the models.

We hypothesized that the increased motor effort resulting from head restriction would induce people to use more memory, and they would continue to use the more efficient strategy in the post-restriction block. Specifically, the number of looks was expected to decrease, the mean look duration to increase, the trial duration and look proportion to decrease. The extent to which participants might change the strategy may be different for different angles.

4.4 Method

4.4.1 Participants and Design

This study used a mixed design. The between-subject factor was the angle at which the model was positioned. Participants were alternately assigned to one of the angles (45° or 135°) and copied the models positioned at the assigned angle on the dominant-hand side for 30 trials. The within-subject factor was block (i.e. pre-restriction, restriction, post-restriction).

Fifty college students were recruited from the introductory psychology class at the University of California, Riverside and received course credit for their participation in the study. Thirteen participants were excluded due to recording problems (e.g. recording device failure, corrupted video files, experimenter error). Another four participants were excluded due to poor pupil image quality for eye tracking. The final sample for the eye tracking data analyses was 33 participants (6 males, 26 females, and 1 other, *M* age = 19.21 years, *SD* age = 1.47), 17 for the angle of 45° and 16 for 135°. All participants had normal or corrected to normal vision and were not color blind. Twenty-eight participants were right-handed, five left-handed. Participants described their ethnicity as Hispanic/Latinx (9) or not Hispanic/Latinx (22); two participants chose not to answer. Participants described their race as Asian (15), White (7), African American (1), More than One Race (1), and Other (3); six chose not to answer.

Among the 33 participants, nine participants were further excluded from the analyses of eye-head-body coordination due to either recording problems (5) or poor synchronization between eye tracking and motion tracking data (3). As a result, the final sample for the motion tracking data analyses was 25 participants (4 males, 20 females, and 1 other, M age = 19.36 years, SD age = 1.55). Among them 14 copied models at the angle of 45° and 11 at 135°.

4.4.2 Apparatus

The experimental setup was the same as in [93] Figure 4.1. Participants stood in front of a music stand which held the *workspace*: an empty 4 × 4 grid with 8 magnets provided for participants to copy the model. The magnets were placed on the side of the grid corresponding to the participant's dominant hand. The *model* was displayed on another music stand which was positioned at the angle of 45° or 135° to the left or right side of the participant. The distance from the participants to the workspace was 35.56 cm (the line 'a'), and was 66.04 cm to the model (the line 'b'). The height of the workspace and model were adjusted to the participant's chest level. The model had a set of 30 different multi-colored patterns (4 colors, 2 magnets each color), which were generated by a computer script and used across all participants in the same order. Two wall-mounted security cameras (on the participants' left and right sides) recorded the third-person view videos.

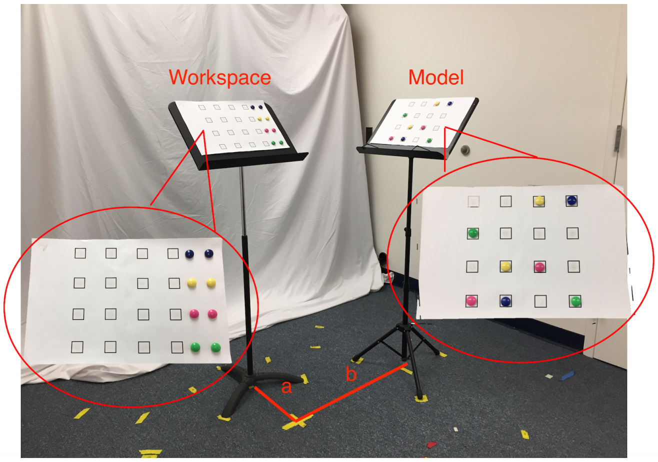


Figure 4.1: The experimental setup.

To capture eye movements, participants wore a Positive Science head-mounted eye tracker (Figure 4.2) throughout the study. The eye tracker has two cameras: a *scene camera* positioned over participants' right eye recording the participants' first-person field of view, and an *eye camera* that points to the participants' right eye and records the eye movements. The two cameras are mounted on a lightweight eyeglass frame. The videos recorded by the two cameras (sampling rate 30 Hz) were streamed to a recording device attached to the shoulder band worn by participants.

To capture head movements, participants wore two wireless STT Systems IWS inertial measurement units (IMUs) (dimensions: 56 × 38 × 18 mm, 46 g): one on the forehead (attached to a head band), the other on the neck (attached to a shoulder band) at the C7 vertebrae (Figure 4.2). The IMUs streamed acceleration and gyroscope data at a rate of 400 Hz over WiFi to the STT software installed on a laptop, which recorded the data.

Figure 4.2: Participants wore a head-mounted eye tracker, which has an eye camera and a scene camera, and two IMUs placed at the forehead and the base of neck were attached to a headband and a shoulder band. Participants wore a neck brace during the restriction block.

In the restriction block, participants wore a neck brace (Figure 4.2). The Aspen Collar neck brace (dimension: 26.67 x 24.13 x 1.78 cm, 159.04 g) is a collar with foam and straps to keep the head from moving from side to side or up and down (sometimes worn by people suffering from whiplash or neck or back pain). Adjustable straps were tightened for a custom fit for each participant.

4.4.3 Procedure

The procedure was the same as in the prior work [94] except participants went through three blocks of 10 trials. In the first and third blocks, participants copied the models without any restriction. In the second, restriction block participants wore the neck brace to restrict head motion while copying the models. In the 1-hour long session, participants were instructed to complete the model-copying task, before and after which they completed brief calibration for the eye tracker and IMUs.

Calibration and Synchronization for the Eye Tracker and IMUs

After giving consent, participants put on a shoulder band, a head band, and the eye tracker. The experimenter adjusted the cameras of the eye tracker to ensure the scene camera would capture the participant's first-person field of view and the eye camera would capture the pupil and corneal reflection no matter how participants moved their eyes. The experimenter attached the IMUs to the headband and shoulder band worn by the participants and ensured they were at the correct positions and orientation.

To calibrate the eye tracker, participants stood 35 cm away from a cardboard poster (76 cm × 51 cm), which was put on the music stand. Nine targets (2.5 × 2.5 cm) were drawn on the board: 4 at the corners, 4 at the midpoints of each edge, and 1 at the center. Participants were asked to move their eyes to look at specific targets while keeping their head still. The eye tracker measured the rotations of eyes while participants were looking at different targets in the field of view and determined the gaze direction in pixels relative to the scene camera video. The same calibration procedure was repeated in the middle and end of the model-copying task to ensure the accuracy of eye tracking throughout the session.

To calibrate the IMUs and to synchronize with the eye tracking data for subsequent analyses, participants were asked to look forward, keep the chin parallel to the floor and still for a while, and then quickly turn the head to the left and right. These motions created identifiable moments in the IMU data to be synchronized with the eye tracking data. The experimenter checked the visualization of the IMUs data on the software to ensure it showed the correct motions.

Model-Copying Task

Participants completed two practice trials and 30 experimental trials of the model-copying task. A set of 30 different configurations of the model patterns were randomly created by a computer script and used across participants. The model was positioned on the side of the participant's dominant hand at the assigned angle (45° or 135°). In each trial, participants were required to copy the model correctly while standing at a designated spot on the floor (the wrongly copied trials were excluded from the data analyses). They were also required to pick up one magnet at one time with the dominant hand. They faced toward the workspace at the beginning of each trial but were allowed to turn their head, body, and feet to look at the model as many times as they needed while copying the model. They were reminded to close their eyes while the experimenters changed the model between trials.

4.4.4 Data Processing and Analyses

Synchronizing the data collected from the eye tracker and IMUs was conducted as in [93].

First, the eye rotation in each frame of the scene videos (in unit of pixels) was calculated from the eye and scene videos recorded by the eye tracker using the software Yarbus (Positive Science). The time series of horizontal eye rotation in pixels were then converted to degrees based on the camera's horizontal field of view and lens correction, as in [45].

Second, the acceleration and gyroscope data recorded by the IMUs were used to calculate the time series of horizontal head rotation in degrees relative to the base of the neck by the software iSen (STT Systems).

Third, to synchronize the eye tracking and IMU data, the experimenter identified the sharp head turns participants made during calibration in the time series of IMU data and the corresponding moments in the scene videos (quick shifts of field of view). The experimenter marked down the times of the head turns and the frame numbers in the videos and then converted the times series to the unit of frames in a Matlab script.

After synchronization, for each frame of the trials in the scene videos, two independent coders tagged each instance of looking at the model. If the participants' eye gaze fell within the area of model in the field of view for at least 2 frames (allowing 1 frame off or a blink in between), a *model look* was defined. The inter-rater reliability was high (98.79%).

To answer the research questions, two sets of analyses were conducted. First, for the IMUs data, a 3-way linear mixed-effect model (LMM) was applied to test the effects of block (3 levels, pre-restriction, restriction, post-restriction), angle (2 levels, 45°, 135°), and segment (3 levels, eye, head, body) on the proportion (%). The block, angle, and segment were included as fixed effects and participant as a random effect in the LMM (proportion $\sim$ block $\times$ angle $\times$ segment + (1 — participant)). Results showed there was a 3-way interaction between block, angle, and segment. To follow up on the block × angle × segment interaction, for each angle, a 2-way LMM predicting the proportion was calculated with block and segment as the independent variables and participant as a random effect for each angle. We conducted the analyses for 45° and 135° separately and then compared between the angle. For clarity, we only reported the results of the two 2-way LMMs below.

Second, for the eye tracking data, four 2-way LMMs were applied to test the effects of block and angle on four dependent measures (i.e., number of looks, look duration, trial duration, look proportion) separately. The block and angle were included as fixed effects, and the participant was included as a random effect in the LMMs. For example, the model used to test the effects on the number of looks was: number of looks $\sim$ block $\times$ angle + (1 — participant).

The *lme4* [11] package in R [110] was used to calculate all LMMs. ANOVAs were used to test significance of main effects and interactions from the LMMs using the *lmerTest* package in R [83]. Degrees of freedom were determined by the Satterthwaite approximation [117, 92]. Follow-up pairwise comparisons used the Holm-Bonferroni correction to adjust for multiple comparisons.

4.5 Results

Two sets of results compared participants' exploratory movements and exploratory strategies across the three blocks. First, to examine how participants coordinated their eyes, head, and body, for each angle separately, we calculated the proportion each segment contributed to make gaze shifts, and compared them between the pre-restriction and restriction blocks, and between the pre-restriction and post-restriction blocks. Afterwards, we compared the differences between the angles. Second, to examine how participants traded off motor effort and use of memory, we compared the number of looks, look duration, trial du-

Table 4.1: Descriptive statistics (*M* and *SD*) for the proportion by block and segment for each angle. Note that the proportions were calculated at the trial level, so the sum of mean proportions is not equal to one.

	45°			**135°**		
	Eye	Head	Body	Eye	Head	Body
Pre-Restriction	.60(.16)	.46(.40)	.28(.31)	.25(.05)	.41(.16)	.34(.17)
Restriction	.73(.16)	.39(.48)	.36(.43)	.28(.04)	.17(.16)	.55(.15)
Post-Restriction	.61(.20)	.46(.40)	.31(.33)	.24(.05)	.43(.21)	.34(.18)

ration, and look proportion between the pre-restriction and restriction blocks, and between the pre-restriction and post-restriction blocks for different angles.

4.5.1 Eye-Head-Body Coordination

The descriptive statistics are shown in Table 4.1. As Figure 4.3 shows, participants increased their eye and body movements to compensate for head movement restriction while wearing the neck brace. Participants resumed their original eye-head-body coordination after removing the neck brace. How participants adapted to restriction depended on the angle of the model: the eyes contributed more to making the gaze shifts and compensating for the head restriction for 45°. In contrast, the body made larger contribution to the gaze shifts and compensation for the head restriction for 135° compared to the eyes.

For 45°, the results of the LMMs (Table 4.2) predicting proportion showed significant main effects of block (3 levels: pre-restriction, restriction, post-restriction) and segment (3 levels: eye, head, body), and an interaction between block and segment. To follow up on the block × segment interaction, pairwise comparisons between the blocks by segment (Table 4.3) showed: the eye proportion increased from the pre-restriction to restriction ($t(1214)$ = 5.218, $p < .001$), then decreased from restriction to post-restriction ($t(1214) = 4.876$, $p <$

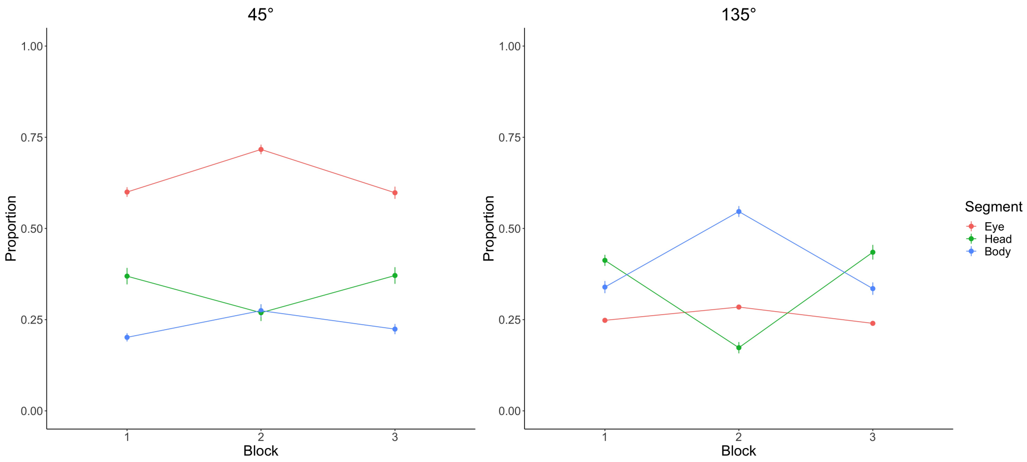


Figure 4.3: The proportion that the eye, head, and body movements (separate colored lines) contributed to the gaze shifts across blocks (x-axis) for different angles (A: 45°, B: 135°). Note that the proportions were calculated at the trial level, so the sum of mean proportions is not equal to one.

Table 4.2: Summary of LMM results predicting proportion from block and segment for each angle.

		45°			**135°**		
	df	*F*	*p*		*F*	*p*	
Block	2	10.06	<.001	***	.04	.959	n.s.
Segment	2	208.92	<.001	***	86.60	<.001	***
Block × Segment	4	7.93	<.001	***	93.48	<.001	***

$^{*}p<.05$, $^{**}p<.01$, $^{***}p<.001$

.001). There was no difference in the eye proportion between the pre- and post-restriction blocks ($t(1214) = .295$, $p = .768$). The head proportions remained similar across the blocks ($p > .05$). The body proportion increased from the pre-restriction to restriction ($t(1214) = 3.669$, $p = .001$), then decreased from restriction to post-restriction ($t(1214) = 2.663$, $p = .016$). There was no difference in the body proportion between the pre- and post-restriction blocks ($t(1214) = .977$, $p = .329$).

Table 4.3: Pairwise comparisons for the proportion between blocks (1: pre-restriction, 2: restriction, 3: post-restriction) by segment for each angle.

	45°	**135°**
Eye	$2 > 1 = 3$	$1 = 2 = 3$
Head	$1 = 2 = 3$	$2 < 1 = 3$
Body	$2 > 1 = 3$	$2 > 1 = 3$

Table 4.4: Pairwise comparisons for the proportion between segments by block for each angle.

	45°	**135°**
Pre-Restriction	Eye > Head > Body	Head > Body > Eye
Restriction	Eye > Head = Body	Body > Eye > Head
Post-Restriction	Eye > Head > Body	Head > Body > Eye

To understand how the eyes, head, and body coordinated in each block for 45°, pairwise comparisons between the segments by block (Table 4.4) showed: in the pre-restriction block, the proportion that the eyes contributed to the gaze shifts was greater compared to the head ($t(1214) = 5.124$, $p < .001$) and body ($t(1214) = 11.488$, $p < .001$). The head proportion was greater than the body proportion ($t(1214) = 6.365$, $p < .001$). In the restriction block, the eye proportion was greater than the proportions of head ($t(1214) = 11.805$, $p < .001$) and body ($t(1214) = 12.906$, $p < .001$). But there was no difference between the head and body proportions ($t(1214) = 1.101$, $p = .271$). The results for the post-restriction were similar to the pre-restriction block: the eye proportion was greater than the proportions of head ($t(1214) = 5.225$, $p < .001$) and body ($t(1214) = 10.606$, $p < .001$), and the head proportion was greater than the body proportion ($t(1214) = 5.381$, $p < .001$).

For 135°, the results of the LMMs (Table 4.2) predicting the proportion showed the main effect of segment and an interaction between block and segment. To follow up on the block × segment interaction, pairwise comparisons between blocks by segment (Table

4.3) showed: the eye proportion remained similar across the blocks ($p > .05$). The head proportion decreased from the pre-restriction to restriction ($t(1214) = 12.202$, $p < .001$), then increased from restriction to post-restriction ($t(1214) = 13.334$, $p < .001$). There was no difference in the head proportion between the pre- and post-restriction blocks ($t(1214) = 1.136$, $p = .256$). The body proportion increased from the pre-restriction to restriction ($t(1214) = 10.529$, $p < .001$), then decreased from restriction to post-restriction ($t(1214) = 10.692$, $p < .001$). There was no difference in the body proportion between the pre- and post-restriction blocks ($t(1214) = .212$, $p = .832$).

To understand how the eyes, head, and body coordinated in each block for 135°, pairwise comparisons between segments by block (Table 4.4) showed: in the pre-restriction block, the proportion that the head contributed to the gaze shifts was greater compared to the body ($t(962) = 3.744$, $p < .001$) and eye ($t(962) = 8.399$, $p < .001$). The body proportion was greater than the eye proportion ($t(962) = 4.655$, $p < .001$). In the restriction block, the body proportion was greater than the proportions of eye ($t(962) = 13.250$, $p < .001$) and head ($t(962) = 18.932$, $p < .001$). The eye proportion was greater than the head proportion ($t(962) = 5.651$, $p < .001$). The results for the post-restriction were similar to the pre-restriction block: the head proportion was greater than the proportions of body ($t(962) = 5.069$, $p < .001$) and eye ($t(962) = 9.911$, $p < .001$), and the body proportion was greater than the eye proportion ($t(962) = 4.820$, $p < .001$).

4.5.2 Motor-Memory Trade-Off

The descriptive statistics are shown in Table 4.5. As Figure 4.4 shows, participants decreased expending motor effort and used more memory to copy the model when the

Table 4.5: Descriptive statistics (*M* and *SD*) for the number of looks, look duration, trial duration, and look proportion by block for each angle.

45°

	Number of Looks	Look Duration	Trial Duration	Look Proportion
Pre-Restriction	12.09(2.97)	.41(.11)	17.43(4.36)	.28(.07)
Restriction	11.24(2.85)	.42(.13)	17.05(4.16)	.27(.07)
Post-Restriction	11.07(2.60)	.42(.10)	15.85(3.26)	.29(.07)

135°

	Number of Looks	Look Duration	Trial Duration	Look Proportion
Pre-Restriction	5.96(2.08)	.86(.36)	23.78(7.92)	.20(.05)
Restriction	5.36(2.08)	.84(.43)	24.41(7.47)	.17(.06)
Post-Restriction	5.49(1.91)	.86(.55)	22.49(7.52)	.19(.08)

head movement was restricted. They continued to use a memory-based strategy even after removing the head restriction. Also, participants further improved task efficiency (less time to complete the task) after removing the restriction although the number of looks and mean look duration were similar as with the head restriction. Compared to the small angle, participants were more likely to use memory and took longer to complete the task when the model was positioned at the large angle.

The results of the LMM predicting the number of looks (the indicator of motor effort) showed significant main effects of block and angle (Table 4.6). Pairwise comparisons on the main effect of block (Table 4.7) showed that the number of looks was greater for the pre-restriction block compared to the restriction ($t(919) = 4.303$, $p < .001$) and post-restriction ($t(919) = 4.768$, $p < .001$) blocks; but there was no difference between the restriction and post-restriction blocks ($t(919) = .457$, $p = .891$). In terms of the angle effect, the number of looks was greater for 45° compared to 135° ($t(31) = 10.702$, $p < .001$).

Table 4.6: Summary of LMM results predicting the number of looks, look duration, trial duration, and look proportion from block and angle.

		Number of Looks			**Look Duration**		
	df	*F*	*p*		*F*	*p*	
Block	2	13.88	<.001	***	.35	.703	n.s.
Angle	1	114.54	<.001	***	21.56	<.001	***
Block × Angle	2	1.84	.160	n.s.	1.06	.346	n.s.

*p<.05, **p<.01, ***p<.001

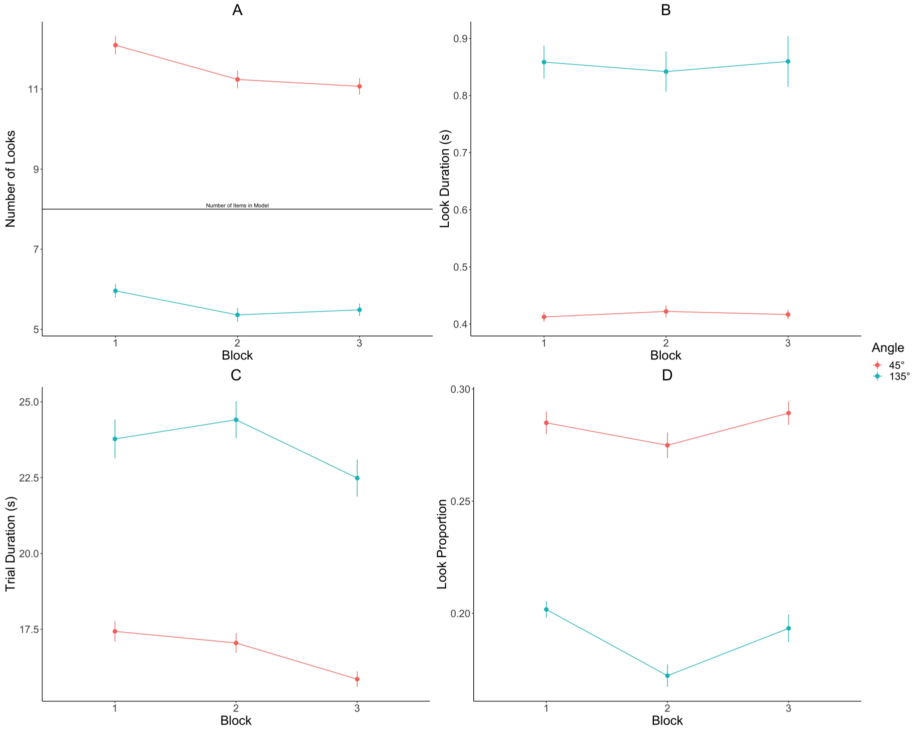
		Trial Duration			**Look Proportion**		
	df	*F*	*p*		*F*	*p*	
Block	2	34.56	<.001	***	17.62	<.001	***
Angle	1	12.05	.002	**	33.32	<.001	***
Block × Angle	2	6.65	.001	**	4.68	.009	**

*p<.05, **p<.01, ***p<.001

Table 4.7: Pairwise comparisons between blocks (1: pre-restriction, 2: restriction, 3: post-restriction) for the number of looks, look duration, trial duration, and look proportion for each angle.

	45°	**135°**
Number of looks	$1 > 2 = 3$	$1 > 2 = 3$
Look duration	$1 = 2 = 3$	$1 = 2 = 3$
Trial duration	$1 = 2 > 3$	$1 > 2 > 3$
Look Proportion	$1 = 2 = 3$	$1 = 3 > 2$

Figure 4.4: Comparisons of (A) the number of looks, (B) mean look duration, (C) trial duration, and (D) look proportion across the blocks (x-axis) for different angles (separate colored lines).



The results of the LMM predicting mean look duration (the indicator of memory use during each model looking) showed a significant main effect of angle (Table 4.6). The mean look duration was shorter for 45° compared to 135° ($t(31) = -4.643$, $p < .001$). There was no significant difference between the blocks ($p > .05$).

The results of the LMM predicting trial duration (the indicator of task efficiency) showed significant main effects of block and angle, and the interaction between block and angle (Table 4.6). Follow up pairwise comparisons on the interaction (Table 4.7) showed that for 45°, the trial duration was lowest for the post-restriction block compared to the pre-restriction ($t(919) = -5.025$, $p < .001$) and restriction ($t(919) = -3.981$, $p < .001$) blocks; but there was no difference in the trial duration between the pre-restriction and restriction blocks ($t(919) = 1.039$, $p = .299$). For 135°, the trial duration for the post-restriction block was the lowest compared to the pre-restriction ($t(919) = -3.408$, $p < .001$) and restriction ($t(919) = -7.285$, $p < .001$) blocks; but the restriction block was longer than the pre-restriction block ($t(919) = 3.911$, $p < .001$).

The results of the LMM predicting mean look proportion (another indicator of task efficiency) showed significant main effects of block and angle, and the interaction between block and angle (Table 4.6). Follow up pairwise comparisons on the interaction (Table 4.7) showed that the look proportion was similar across block for 45° ($p > .05$). However, for 135°, the look proportion was lower for the restriction block compared to the pre-restriction ($t(919) = -5.842$, $p < .001$) and post-restriction ($t(919) = -4.474$, $p < .001$) blocks; there was no difference between the pre- and post-restriction blocks ($t(919) = 1.382$, $p =.167$).

4.6 Discussion

This study investigated whether inducing people to explore different strategies leads them to adopt a more efficient strategy later. Specifically, we restricted participants' head movement by having them wear a neck brace, and investigated if the head restriction leads participants to use more memory in a copying task. The results showed that the head restriction changed the eye-head-body coordination such that the eyes made a larger contribution to smaller gaze shifts whereas the body made larger contribution to larger gaze shifts. In terms of the copying strategy, the increased motor cost caused by the head restriction led people to use more memory (as indicated by the decreased number of looks), and the effect carried over to the post-restriction block—participants continued to use more memory and improve the task efficiency after removing the head restriction.

4.6.1 Changes in Eye-Head-Body Coordination

A novel aspect of the study was that we directly altered how the eyes, head, and body coordinated. Results showed that participants changed their eye-head-body coordination with the head restriction, indicating a successful manipulation on the effort of moving the head. Specifically, when the head was restricted, both the eyes and body increased their movements. But the eyes compensated more for the gaze shifts of small amplitude. When larger amplitude was required, the eyes did not rotate to extreme positions. Instead, the body moved to account for the large proportion of the gaze shifts although the body movements were more costly. This finding was consistent with the center bias found in other studies [16, 45]—observers are biased to keep their eyes relatively centered within their orbits, well below the anatomical limit of movement.

It is noted that the original eye-head-body coordination was resumed after removing the head restriction. That is, although participants adopted a different coordination of the eyes, head, and body to compensate for restriction, the original eye-head-body coordination was more efficient (or preferred). It also indicated that the strategy changes after the head restriction (discussed in next section) could not be explained by how the eyes, head, and body coordinated.

4.6.2 Changes in the Copying Strategy

Previous studies showed that different factors affect the motor-memory trade-off such as the motor effort of moving the eyes, head, and body to gather visual information [9, 26, 55, 70, 93, 85, 59, 106]. Consistent with that, the current study found that participants chose to use more memory when the motor cost of moving the head increased. Moreover, we found that participants continued using more memory after removing the head restriction, indicating a carry-over effect of exploration [68]. Specifically, participants looked less frequently to the model. Although the number of looks and mean look duration remained similar after removing the head restriction compared to with the head restriction, the trial duration continued decreasing, indicating improved efficiency. It is possible that participants might move the eyes, head, hands, and body more quickly to copy the model. Future studies could capture the hand movements and investigate how the eye-hand coordination might change.

However, the conclusion about the carry-over effect should be interpreted cautiously. The number of looks in the post-restriction block was similar to the number of looks at the end of multiple trials practicing the copying task [94]. The carry-over effect of strategy exploration observed in the current study might be due to mere practice, not the result of head restriction. Specifically, the mean number of looks in the post-restriction block for the small angle was about 11, which was still higher than the number of items (i.e. 8) on the model. In other words, participants could potentially memorize the position of each item and copy them one by one—in which case they only needed to look at the model 8 times. But they used the minimum memory and kept checking the positions of items visually back and forth. The similar strategy was observed after spontaneous repeated practice as in [94]. The findings were consistent with the previous studies showing that people tend to rely on motor effort to complete tasks [9, 26, 55, 70, 93]. It is possible that compared to motor effort, the use of memory is more expensive and delicate [98, 23, 61, 14]. Future studies could investigate whether time constraints, feedback, or the teaching of memory skills might lead people to use more cognitive resources.

4.6.3 Conclusion

The current found that with head restriction, people coordinate the eyes, head, and body differently and discover a more efficient strategy—using more memory rather than motor effort, to copy information. After removing the head restriction, the eyes, head, and body revert to how they coordinate originally. Given the same amount of motor effort (compared to pre-restriction), people continue to use the memory-based strategy afterwards and copy the information efficiently. But we did not test if the improved performance in the post-restriction block is more attributed to strategy exploration or mere practice. Also participants could potentially further improve efficiency by memorizing more information in one model look. The findings enhanced our understanding about how the motor effort of moving the eyes, head, and body may affect people's use of memory. Future studies could investigate the developmental changes in strategy exploration and motor-memory trade-off.

Chapter 5

Conclusions and Future Directions

This dissertation investigated the motor-memory trade-off and the underlying coordination of eyes, head, and body. Regarding the motor-memory trade-off, Chapter 2 showed that participants tended to expend more motor effort when the cost of movement was low, but used more memory when the cost of movement was high. Chapter 3 showed that participants changed the copying strategy by using more memory after repeated practice with the task to become more efficient. Chapter 4 showed that participants discovered and adopted a more efficient memory-based strategy after exploring the strategy space to cope with head restriction. Regarding the eye-head-body coordination, Chapter 2 showed that the eye movements contributed most to make gaze shifts of small amplitude, but head and body movements made greater contribution for gaze shifts of large amplitudes. Chapter 3 showed that with repeated practice, participants increased the proportion of head movements to reduce the need to make costly body movements at small angles; eye-head-body coordination was not changed with practice at larger angles. Chapter 4 showed that the eye-head-body coordination was altered by head restriction but was resumed after removing the head restriction, indicating the original eye-head-body coordination might be more efficient or comfortable.

The current studies replicated past work that participants adapt the motor-memory trade-off to task constraints [9, 26, 55, 70, 85, 59, 68, 106], indicating the dynamic interaction between motor and cognitive systems. When motor cost is high, people use more memory. When memorization is difficult, people rely on their motor abilities. This demonstrates that people can exploit resources flexibly according to the current situation.

A novel contribution of the current studies is showing how the motor-memory trade-off evolves over time. It is surprising that in a well-practiced task—looking back and forth to gather information—in a sample of typical adults, that there would be room for improvement. Participants did not stick with the same strategy that they adopted when first encountering the task. Rather, they kept adjusting the motor-memory trade-off trial-by-trial while practicing the task, despite there being no time pressure or reward to motivate participants to improve. This may indicate that people are spontaneously motivated to adjust their strategy to save energy. Moreover, the current studies showed that people learn and adopt more efficient strategies after being induced to explore different strategies. The learning ability makes people more adaptive to the changing environment.

Another novel contribution of the currents studies is showing how people change the coordination of different segments in their own body to adapt to the tasks, when there are multiple degrees of freedom to control. We found people coordinate their eyes, head, and body in different ways to make gaze shifts of different amplitudes. When one effector is restricted, they employ other effectors to compensate for the restriction. When the restriction is removed, they revert to the more efficient or comfortable way. In addition, they keep adjusting the eye-head-body coordination on the go while doing the task. People are motivated to use lower-effort movements to reduce higher-effort movements spontaneously. Those findings could not be observed if we simply treat motor effort as an angle or distance. The underlying eye-head-body coordination provides insight into the motor control system, and how it may relate to the motor-memory trade-off.

5.1 Implications for the Degrees of Freedom Problem

An ongoing debate in the study of motor control is how people solve the degrees of freedom problem [12]. Most complex movements can be performed in a variety of ways. For example, to make a gaze shift of 20°, people could move their eyes for 20° without moving their head and body. Or they could move their eyes for 10° and move their head and body for 5° each (or many other allocations). With a variety of possibilities, how do people select a specific way to perform the movements? What drives the motor decision? One hypothesis is that people solve the degrees of freedom problem by choosing the most efficient strategy [118]. However, the opposite was observed in the current studies—people do not always choose the most efficient or energetically economical strategy. The current studies raise a specific challenge to the Optimal Control Hypothesis [118].

Results indicated that people coordinate their eyes, head, and body in an energetically inefficient way. For example, the oculomotor range of human eyes is about 55°. That is, people could rotate only their eyes to 55° horizontally. But we found in the current studies that to make gaze shifts of 45°, people move their head and body for about 20°, contributing to nearly half of the rotation. Moving eyes more to reduce costly head and body movements would efficiently save a lot of motor effort as they make gaze shifts so frequently. But people do not perform in the most efficient way, suggesting the need to identify another constraint to optimize. Possibly, eye-head-body control may take into account both energetic efficiency and exploration utility. For example, Tatler hypothesized that people might avoid making extreme eye movements because they limit future exploration [128]. This points to a key difference separating the current work from previous work about motor control—whereas performatory movements (e.g., reaching, stepping) might be optimized for efficiency, exploratory movements might be optimized for information gain at the cost of energetic efficiency.

However, some aspects of participants' behavior might not have been optimized in any way. For example, the current studies found that participants looked at the model 10 times on average to copy a model consisting of 8 items. Eight model looks would be sufficient if participants copied 1 item at a time. Moreover, people were highly consistent this inefficient behavior, despite multiple degrees of freedom in both the trade-off strategy and eye-head-body coordination. The results across all three studies replicated that participants expended more motor effort than necessary even after repeated practice or when the head was restricted. In summary, the current studies are consistent in showing that if participants are optimizing something to solve the degrees of freedom problem, it is not energy. But an even stronger challenge to the optimal control hypothesis comes from these extra looks to the model; even in a highly practiced task, participants were consistent in making unneeded exploratory movements.

Another way to approach the problem of inefficiency is to investigate the impact of metacognition in the task. One possibility is that participants did not believe that they were doing the task accurately, so they felt the need to override the efficient strategy and look at the model more than was necessary. Future studies should explicitly test if people are aware of what strategies they are using and what might be more efficient. In a prior computer-based study [68], participants were instructed to copy a number of messages from one page to another in specific ways (for example constrained to look at 1 message at a time). They were also provided the feedback of their performance in each trial. Results showed that participants produced the highest efficiency when remembering 5 messages at a time. They also chose to use this strategy when allowed to approach the task freely later. But it is unknown whether the memorization difficulty of the messages was comparable to the model patterns in the current studies. Future studies could design a computer version of the current studies to manipulate the numbers of looks and copies allowed in a trial. In this way, participants' performance profiles could be established to examine the most efficient strategy for individuals and whether increasing people' awareness of strategy use would help them improve efficiency.

5.2 Implications for Development

An intriguing avenue for future research is to examine how children navigate the motor-memory trade-off. Although only adults were tested in the current studies, the task is suitable for young children (about 5 or 6 years of age). Taking a developmental approach provides one potential avenue for disentangling the components that contribute to efficiency/inefficiency in the motor-memory trade-off. Regarding motor abilities, even toddlers demonstrate an adult-like ability to move their eyes and head in concert [25], suggesting that the ability to coordinate might not present age differences. By the age of 2, children have developed fine motor skills such as reaching, grasping, and manipulating objects with hands [1]. Thus, the motor movements required to perform the puzzle completion task should not be taxing for children. Instead, age differences in children's cognitive abilities or the efficiency of their visual-motor planning might play a role.

In terms of memory span, the normative developmental data showed that children by 6 years of age can memorize a sequence of 5 items, compared with 7 for adults [34]. Even though children's memory span is less than adults', it should still allow children to memorize 2-3 items each time they look at the model in the copying task. Yet, in certain conditions we observed that adults were unwilling to memorize even that much. By comparing children's and adults' willingness to memorize compared to their memory span, we may be able to determine whether model looks scale to memory abilities. Alternatively, memory ability may be uncoupled from how people spontaneously choose to memorize items in the task.

Another developmental difference between children and adults might be how they manage cognitive and motor effort in an efficient way. Recent work indicated that children as young as 5 years are sensitive to some aspects of the type and intensity of their own efforts. In the study, 5-year-olds built toys by doing different tasks and were tested how long they were willing to wait in order to get the toys in the end [78]. The tasks varied in the type (i.e. cognitive vs. physical) and intensity (i.e. high vs. low effort). It is found that children were more willing to wait for the toys built through cognitive and low-effort tasks compared to physical and high-effort tasks. Although it was unclear how children reasoned about their decision, the finding suggested that by 5 years of age children may differentiate the type and intensity of their own efforts.

How do children learn to trade off motor effort and memory use efficiently? Do they learn to become more efficient through practice? The current studies suggested that people become more efficient after exploring different strategies. Could strategy exploration facilitate child learning of the motor-memory trade-off? Past work demonstrated that children's willingness to explore strategies changes with age [41]. Younger children (4-7 years) were found to be more willing to try different ways of doing a motor task compared to older children (8-11 years) [41]. Older children were more cautious and avoided making mistakes. However, younger children did not perform better than older children in the task. It is possible that children may have difficulty learning from their mistakes and discovering the most efficient strategy after exploration [88, 41, 72]. Future studies should research the developmental changes in the effect of strategy exploration on the motor-memory trade-off.

Developmental differences in motor versus cognitive expertise across the lifespan might guide how participants trade off. Many aspects of visual and motor control reach adult-like levels by early childhood [1], well before cognitive abilities become adult-like. How might the a greater imbalance between motor and cognitive abilities affect the motor-memory trade-off? It is possible that individuals might overly exploit the more developed ability. For example, children may need to expend more motor effort than adults to gather information. In contrast, individuals with restricted motor abilities (for example, people coping with temporary injury or long-term movement disabilities) may rely more on cognitive abilities. Declining motor and cognitive abilities in the process of healthy aging provides another interesting avenue for future research—would older adults still be willing to expend more motor effort to avoid memorization?

Given the motor and cognitive systems dynamically interact with each other, how does the reliance on more advanced ability to complete tasks affect the development of other abilities? Previous studies suggested that children's early motor development has cascading effect on cognitive development [124, 103, 102, 133, 134]. The onset of walking broadens infants' visual experiences [81], elicits different language input from caregivers [75], and facilitates social interaction [74, 44]. In all of these examples, the cascading effect of motor development on cognitive and social development is theorized to depend on how new motor skills increases exploratory abilities. Walking allows infants to travel to new places, and an upright position allows infants to look in greater directions. In the same way, adults in the current study relied on visual exploration to aid their cognitive performance. Assessing the developmental course of whether visual exploration is *efficient* might have other implications for cascading effects on cognition.

Recent work has found links between motor skills and academic performance, including both numeracy and literacy [17]. For example, children who develop fine motor skills (e.g. finger dexterity) use fingers to understand the concepts of numbers and do algebra [35, 50, 54, 49]. Literacy is linked to children's learning of handwriting, which in turn is linked to their visual-motor abilities [36]. Like the task used in the current studies, learning to write requires children to look at a letter to memorize its shape, and then look at a different place to reproduce the letter while guiding the pencil. When studying children's model looks while completing a handwriting reproduction task, Fears and colleagues [36] found that children did not spend more time looking at more complex displays, in contrast to the difficulty effect we observed in Chapter 2. This suggests that learning to efficiently use visual-motor skills in conjunction with memory may be a critical development in learning to write. Measuring age differences in the block copying task in parallel with the development of handwriting may shed light on whether visual-motor efficiency has cascading effects on academic achievement.

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