

Learning to Efficiently Gather Visual Information Using the Eyes, Head, and Body

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## Abstract

People move their eyes, head, and body to gather visual information for everyday tasks. However, it is unknown whether and how people adjust their eye-head-body movements over time to adapt to task parameters. This study investigated how people changed their information-gathering strategy—how they moved their eyes, head, and body to look—after repeated practice (Experiment 1) and after exposure to new strategies (Experiment 2). In Experiment 1, participants were asked to copy models over repeated trials to test the effect of practice. We recorded participants' eye-head-body movements while copying models. We calculated how frequently they looked at the models, the total time used to complete each trial, and the eye-head-body rotations during model looks. The results showed that people looked less frequently and reduced the effortful body movement to improve efficiency after repeated practice. The same task was used in Experiment 2 except that we restricted participants' head movement while copying the models and then removed the restriction to induce strategy change. The results showed that participants opted for a less effortful strategy during head restriction and retained the effort-saving strategy after head restriction was removed.

## Learning to Efficiently Gather Visual Information Using the Eyes, Head, and Body

People need to move their eyes, head, and body to gather visual information for everyday tasks (Land, 2004). For example, to change lanes while driving, the driver needs to look in different directions to check the cars ahead, behind, and in the blind spot. Because gathering visual information takes time and motor effort, it is costly (Ballard, Hayhoe, & Pelz, 1995; Draschkow, Kallmayer, & Nobre, 2021; Luo & Franchak, 2022). Balancing informational needs and exploratory cost creates a trade-off. If a driver spends too much time to check in all directions, they may miss the best opportunity to change lanes. But if the effort of looking over shoulder leads the driver to skip checking the blind spot, they may make a dangerous decision. Thus, moving eyes, head, and body to gather information efficiently is important for executing tasks successfully. Although much prior work has characterized how people spontaneously gather visual information in a variety of tasks (Ballard, Hayhoe, Li, & Whitehead, 1992; Ballard et al., 1995; Einhäuser et al., 2007; Foulsham, Walker, & Kingstone, 2011; Franchak & Adolph, 2010; Franchak, McGee, & Blanch, 2021; Geruschat, Hassan, & Turano, 2003; Hayhoe, 2000; Hayhoe, Shrivastava, Mruczek, & Pelz, 2003; Land & Furneaux, 1997; Land & Hayhoe, 2001; Land & Lee, 1994; Land & McLeod, 2000; Land, Mennie, & Rusted, 1999; Matthis, Yates, & Hayhoe, 2018; Rothkopf, Ballard, & Hayhoe, 2007; Tomasi, Pundlik, Bowers, Peli, & Luo, 2016; Turano, Geruschat, & Baker, 2003; Turano, Geruschat, Baker, Stahl, & Shapiro, 2001; Underwood, Chapman, Brocklehurst, Underwood, & Crundall, 2003), past research has focused on exploration in aggregate rather than how it changes over time. How do people learn within a task to adapt their information-gathering strategy to task parameters? The current study aimed to investigate how people spontaneously adjust their information-gathering strategy (i.e., the ways they move their eyes, head, and body to look in different directions) over time to gather information more efficiently.

Some previous studies showed that people do not always settle on efficient information-gathering strategies when spontaneously choosing how to perform a task (Ballard et al., 1995; Draschkow et al., 2021; Franchak & Somoano, 2018; Labinger,

Monson, & Franchak, 2018; Luo & Franchak, 2022). For example, Ballard and colleagues found that people tended to over-expend information-gathering effort in a copying task (Ballard et al., 1995). In the study, participants were asked to copy models comprised of a patterned set of items (e.g., squares or circles of different colors). When copying models, participants looked at the models more frequently than was necessary: They chose to copy one item at a time and continued looking back and forth repeatedly. Other work showed that participants were capable of memorizing four items and copying them correctly in just a single look, which saved time and energy (Ballard et al., 1992). Yet, when allowed to spontaneously choose how to visually explore the models, participants avoid holding multiple items in memory by frequently looking at the model (Ballard et al., 1995).

Past work investigated whether increased cost of looking led to a change in people's information-gathering strategy (Luo & Franchak, 2022). In the study, the motor cost of looking was manipulated by placing the models at different angles around the participants in the copying task (Ballard et al., 1995). Participants' eye-head-body movements were recorded to examine the amount of effort they chose to expend—for a given motor cost angle, choosing to look more times exerts more effort. Results showed that people used different strategies to gather information from the models positioned at different angles. When the models were at a small angle (i.e., costing less to look), participants looked at the models frequently and relied on eye movements to make gaze shifts. When the models were at a larger angle (i.e., costing more to look), participants looked less frequently and relied on more effortful head and body movements to shift their gaze. Thus, the motor cost of moving eyes, head, and body to look influenced how people spontaneously chose to gather visual information. However, even for larger angles where participants needed to make large head and body movements to look at the model, participants still used the “look often, remember little” strategy: Frequent eye-head-body movements were used to look at the model while memorizing only 1-2 items each time.

One possible explanation for their over-expenditure of motor effort was that

participants did not have enough practice to optimize their strategy. In the study (Luo & Franchak, 2022), the model was placed at different angles from trial to trial, which might prevent participants from learning how to optimize movements within a single set of task parameters. However, there is abundant evidence that people improve their performance after repeated practice in different tasks (Chen, Hendrick, & Lidor, 2002; Chiviawowsky & Wulf, 2002; Chiviawowsky, Wulf, de Medeiros, Kaefer, & Tani, 2008; Gehringer, Arpin, Heinrichs-Graham, Wilson, & Kurz, 2019; Martin, Keating, Goodkin, Bastian, & Thach, 1996). For example, some studies found that after practice, participants changed body coordination to make movements smoother and less effortful. For example, in a large-scale visual searching task, participants restricted head movement at the beginning but learned to coordinate the eyes and head later to improve efficiency in the task (Fang, Nakashima, Matsumiya, Kuriki, & Shioiri, 2015). Another study found that novice participants learned to coordinate complex dance moves by themselves within multiple trials (Eaves, Breslin, & van Schaik, 2011). Thus, we predicted that people might learn a more efficient strategy after repeated practice.

However, other work about strategy change shows that participants might stick with their initial strategy, which could be inefficient, without adapting it to the changing task conditions over time. For example, in a prior study (Leroy, Koun, & Thura, 2023), 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 parameters subtly changed and they made more errors later. That is, participants failed to monitor their performance, so they did not realize that their initial strategy was no longer adaptive later on. However, other studies found opposite effects. In a problem-solving task, without even receiving hints participants shifted to more efficient strategies with experience (Simon & Reed, 1976). Participants changed from algorithmic processing to a memory-based strategy in an associative learning task (Kuhns & Touron, 2020). Participants learned to trade off

between information collection and reward-taking actions in a gambling game and made better decisions with practice (Navarro, Newell, & Schulze, 2016). Children also demonstrated strategy change in solving mathematical problems (Alibali, 1999; Lemaire & Lecacheur, 2010). For the trade-off between a mental and physical task, prior work shows that people find mental effort aversive (David, Vassena, & Bijleveld, 2024) and that people subjectively weigh how to balance mental and physical efforts (Fegghi & Rosenbaum, 2019).

A second potential explanation for inefficiency is that although participants had enough opportunity to learn, they did not take advantage of repeated practice to test and explore different strategies (Lee, Farshchiansadegh, & Ranganathan, 2018). Exposing people to different strategies might lead them to adopt a more efficient one. In one example (Howes, Duggan, Kalidindi, Tseng, & Lewis, 2016), participants were asked 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 copy certain numbers of appointments (from 3 to 9) at a time to the calendar. Afterwards, participants went through the choice phase in which they could decide how many appointments to copy each time opening the email. Results showed that the number of appointments participants chose to copy 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 being exposed to different strategies.

### **Current Study**

The current study aimed to investigate how people spontaneously change their strategy according to the motor cost of eye-head-body information-gathering movements. Observing whether people adjust spontaneously to become efficient approximates real-world behavior in which there is no explicit instruction on how to perform a task. The current study included two experiments. Experiment 1 investigated the effect of repeated practice on participants' information-gathering strategy ("strategy" for conciseness). Experiment 2 examined the effect of strategy

exposure—exposing participants to new strategy by restricting their head movements. We recorded participants' eye-head-body movements to examine whether people changed strategy and became more efficient over trials of repeated practice (Experiment 1) and after trying different strategies induced by restricted head movements (Experiment 2). The copying task in Experiment 1 and 2 was the same and modeled off Ballard's study (Ballard et al., 1995). Participants were instructed to copy models while wearing a mobile eye tracker and two motion sensors to record their eye and head movements. We manipulated the motor cost of looking by placing the models at different angles around participants (four angle conditions in Experiment 1: 45°, 90°, 135°, 180°; Two angle conditions in Experiment 2: 45°, 135°). Each participant completed all trials at one assigned angle, allowing us to test whether they improved efficiency over trials under similar condition. Comparing between participants assigned to different angle conditions allowed us to examine whether the increased motor cost at larger angles spurred participants to improve their efficiency more compared to participants who completed the less costly task at small angles. It is possible that participant might adopt a strategy with fewer looks when the cost of each look is greater (i.e., at large angle conditions).

We characterized participants' strategy based on the *number of looks* and *trial duration*. A greater number of looks—how many times participants looked at the model in a trial—meant that participants chose a strategy that expended greater motor effort. Shorter trial duration—the total time participant spent in completing the task for each trial—meant participants completed the copying task more quickly, that is, with higher efficiency. If participants changed their strategy to become more efficient after repeated practice in Experiment 1, we predicted that the number of looks and trial duration would decrease over the course of trials. We expected these effects to be stronger for participants assigned to the larger angle conditions where each look cost more energy.

Experiment 2 tested whether exposing participants to a different strategy by limiting head movement would increase efficiency. Whereas Experiment 1 manipulated motor cost by changing the location of the model, Experiment 2 varied both the

location of the model and the cost of head movements. Based on a prior study (Luo & Franchak, 2022), the range of eye rotation was too small to shift gaze to gather visual information on the models positioned at large angles. Thus, with head movement restricted, participants had to rely more on body movements to gather visual information, resulting in higher motor cost of each look because body movements are more effortful than eye movements. In the study, participants completed three blocks of trials at one assigned angle: 1) a pre-restriction block of copying trials without a neck brace; 2) a restriction block of trials wearing a neck brace; 3) a post-restriction block of trials without a neck brace. It allowed us to determine whether exposing people to greater motor cost (due to head restriction) led them to spontaneously discover and adopt a more efficient strategy by memorizing more items at a time. We predicted that participants would change the strategy and further improve efficiency in the post-restriction block after head restriction was removed compared to the pre-restriction block. Importantly, we did not tell participants that the head movement restriction was intended to change their strategy use, which would be a confound if we were to test whether an explicitly-instructed strategy was retained in the post-restriction block.

Independent of strategy (i.e., number of looks), it is possible that participants might improve efficiency by optimizing their eye-head-body movements involved in looking. For example, body movements are slower and more effortful than head movements, and head movements are slower and more costly than eye movements, participants could potentially improve their efficiency by rotating the eye to a greater extent, reducing the amount of rotation of head and body. To explore the possibility, we used a second set of dependent measures to test if participants optimized their eye-head-body movements over trials. As in (Luo & Franchak, 2022), we measured horizontal *eye rotation* from a wearable eye tracker, *head rotation* from wearable inertial sensors, and *body rotation* at the moment of looking at the model. We hypothesized that people would change their strategy and/or eye-head-body movements to become more efficient after practice (Experiment 1) and exposure to new strategies (Experiment 2). We considered strategy and movement efficiency as two different aspects of the

strategy that might improve—it is possible for both to change or for either one to change independently of the other.

### **Experiment 1: Improving Efficiency after Repeated Practice**

#### **Method**

**Design and Participants.** 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 angle conditions ( $45^\circ$ ,  $90^\circ$ ,  $135^\circ$ ,  $180^\circ$ ) 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 and trial duration from trial to trial using wearable eye tracking data, and measured the eye, head, and body rotations using wearable eye tracking and inertial sensing data.

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. Eleven participants were excluded due to an eye tracking recording device failure, and another three participants were excluded due to poor eye tracking data quality. The final sample for the eye tracking data analyses was 48 participants (17 males, 25 females, and 6 chose not to report,  $M$  age = 19.3 years,  $SD$  age = 1.50), 9 for the angle of  $45^\circ$ , 15 for  $90^\circ$ , 10 for  $135^\circ$ , and 14 for  $180^\circ$ . 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 excluded from the analyses of eye-head-body movements based on the quality of the motion tracking data. Ten were due to synchronization problems between eye tracking and motion tracking data; one was due to 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  $45^\circ$ , 11 at  $90^\circ$ , 9 at  $135^\circ$ , and 8 at  $180^\circ$ .

**Apparatus.** The apparatus was the same as in (Luo & Franchak, 2022). Two music stands were set up as Figure 1A shows. One music stand served as a *workspace* providing participants with an empty sheet of  $4 \times 4$  grid and 8 magnets to copy models. Another music stand held the model and was positioned at one of the angles ( $45^\circ$ ,  $90^\circ$ ,  $135^\circ$ , or  $180^\circ$ ) on the participant’s dominant hand side (44 out of 48 participants were right-handed). The distance from the participant to the workspace was 35.56 cm (the line ‘a’) and was 66 cm to the model (the line ‘b’). The height of both music stands was adjusted to each participant’s chest level. A set of model patterns was generated by a computer script that randomly placed 8 magnets (4 colors, 2 magnets each color) on a  $4 \times 4$  grid. All participants went through the same 16 trials of different patterns in the same order.

Throughout the study, participants wore a Positive Science head-mounted eye tracker and two wireless STT Systems IWS inertial measurement units (IMUs) (left image in Figure 1B). The eye tracker and IMUs were the same as in (Luo & Franchak, 2022). The eye tracker recorded two video files at a sampling rate of 30 Hz: an eye video (i.e., a recording of participant’s eye movements) and a scene video (i.e., a recording of the scene from participant’s viewpoint). The IMUs measured the linear acceleration and angular velocity of head movements at a rate of 400 Hz. The data were streamed over WiFi to the STT software installed on a PC laptop.

**Procedure.** After giving consent, participants wore a head-mounted eye tracker and two motion sensors with the assistance of experimenters. Participants were then given detailed task instructions: *“In the task, you will copy 16 models to the workspace. The model will be placed at the assigned angle. To copy the model, you can only pick up one magnet at a time with your dominant hand. You are allowed to freely move your head, body, and feet to look at the model as many times as you want. There is no time limit but please make sure you copy the model correctly. We will remind you to face*

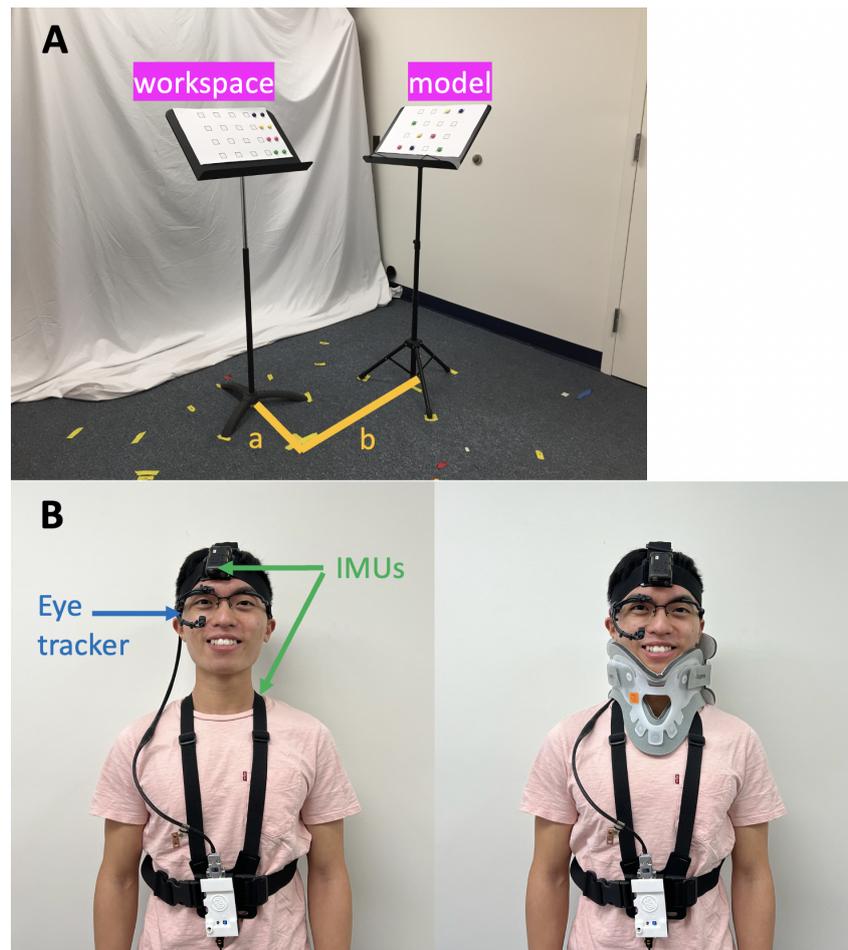


Figure 1. A) Model-copying apparatus showing an example trial in which the model was positioned  $90^\circ$  from the workspace. B) Left image shows a participant wearing a head-mounted eye tracker and two inertial movement units (IMUs) placed at the forehead and the base of neck. Right image shows the neck brace worn during the restriction trials in Experiment 2

*toward the workspace and close your eyes when we switch the models. We will ask you to open your eyes when the models are ready for you to copy. Let us know when you are done. We will change the model for next trial.*" Participants practiced the task to ensure they followed the instructions correctly; the practice trial was not analyzed.

Before starting the real trials, participants performed the calibration and synchronization procedure for the motion sensors and eye tracker. Specifically, participants were asked to keep their head still for a while and then turn their head to the left and right as quickly as possible without turning their body. The movements

caused sharp changes in the scene video and motion sensor data, which were used as synchronization points between the eye tracker and motion sensors later. The experimenters also checked whether the readings and visualization of IMU data in the STT software corresponded to the expected motion.

Next, participants were asked to move their eyes only (without moving their head) to look at different locations across a board placed in front of them to calibrate the eye tracker. Once the calibration was conducted, participants went through 16 trials of copying task. The same calibration and synchronization procedure was conducted at the end of the study to ensure data accuracy throughout the session.

**Data Processing and Analyses.** Data processing was the same as in (Luo & Franchak, 2022). First, the eye tracking and motion sensor data were synchronized. Human coders identified the sharp shift in the scene video and the corresponding head movement in the motion sensor data. Based on those synchronization points, the motion sensor data were offset and then downsampled to 30 Hz to match the time series of eye tracker.

Second, head movement data were extracted from IMUs using the software iSen (STT Systems). iSen software calculates head rotation relative to the C7 vertebrae on the spine using a proprietary algorithm.

Third, the eye gaze in every frame of the scene videos was detected by superimposing the eye videos over the scene videos using the software Yarbus (Positive Science). The raw eye position data points in each frame (in pixels) were extracted and converted to degrees based on the camera's horizontal field of view using the Matlab Camera Calibration toolbox .

Fourth, coders identified the beginning and end of each trial in the scene videos: The beginning of a trial was the moment when participant opened their eyes; the end of a trial was the moment when participant said they were done. Two independent coders went through every frame of the 16 trials and coded the eye gaze location for each frame. If eye gaze fell within the area of the model in the scene videos for 2 or more frames (66.6 ms), those frames were defined as a *model look*. The inter-rater reliability

was 97.7% agreement.

Fifth, the horizontal eye rotation (within the head) and the horizontal head rotation (of the head relative to the torso) during model looks were extracted from the raw eye and head movement data. The absolute values of the eye and head rotations were taken to avoid left and right movements canceling each other out. The corresponding body rotation during model looks was estimated by subtracting the eye and head rotations from the angle of the trials.

Last, we calculated two sets of dependent variables (DVs) for different trials to capture participants' strategy and eye-head-body movements.

For strategy, we calculated *number of looks* and *trial duration*:

1. *Number of looks*: the total number of model looks in a trial. A larger number of looks meant that participants more frequently moved their eyes, head, and body to look at the models, indicating effortful strategy use.
2. *Trial duration*: the total time spent in completing each trial. A shorter trial duration indicated higher efficiency.

For eye-head-body movements, we calculated eye-head-body rotations angles:

1. *Eye rotation*: the mean in degrees of the absolute horizontal eye rotation during moments when the participant was looking at the model (model looks) in a trial.
2. *Head rotation*: the mean in degrees of the absolute horizontal head rotation during the model looks in a trial.
3. *Body rotation*: the mean in degrees of the estimated horizontal body rotation during the model looks in a trial.

For data analyses, we focused on changes of the DVs over trials and whether motor cost (i.e., angle condition) influenced the changes in strategy and eye-head-body movements. All data and analysis code are available on OSF ([https://osf.io/wdx73/?view\\_only=9524023bd92b41dbaee79e9b1ead0bf3](https://osf.io/wdx73/?view_only=9524023bd92b41dbaee79e9b1ead0bf3)). Thus,

five 2-way linear mixed-effect models (LMMs) were applied to test the effects of trial and angle on DVs separately. Trial and angle 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  $\sim$  trial  $\times$  angle + (1 | participant).

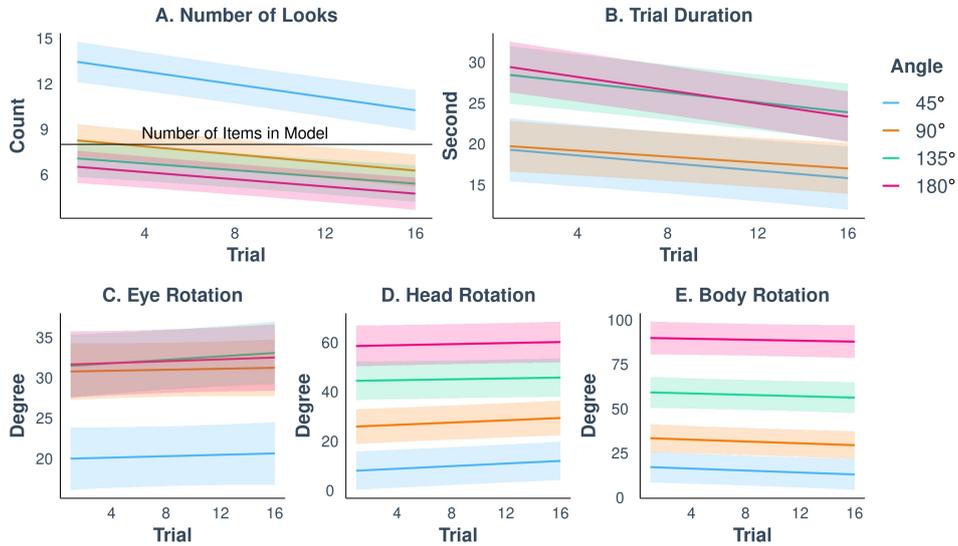
The *lme4* (Bates, Mächler, Bolker, & Walker, 2014) package in R (R Core Team, 2019) was used to calculate all LMMs. ANOVAs were used to test significance of main effects and interactions from the LMMs using the *lmerTest* package in R (Kuznetsova, Brockhoff, & Christensen, 2017). Degrees of freedom were determined by the Satterthwaite approximation (Luke, 2017; Satterthwaite, 1941). Follow-up pairwise comparisons used the Holm-Bonferroni correction to adjust for multiple comparisons.

### Experiment 1 Results

As predicted, participants changed their strategy to improve efficiency after repeated practice. We report two sets of results—changes in strategy (number of looks and trial duration) and changes in movements (eye rotation, head rotation, and body rotation).

**Strategies Changed with Practice.** As Figure 2 A-B shows, participants looked fewer times and completed the task more quickly over successive trials. Comparing trial 1 to 16, the mean number of looks dropped from 14.0 to 10.5 at 45°, from 9.5 to 6.4 at 90°, from 8.3 to 4.2 at 135°, and from 7.5 to 4.8 at 180°. From trial 1 to 16, trial duration decreased by a mean of 6.5 s at 45°, 4.8 s at 90°, 9.4 s at 135°, and 11.1 s at 180°. Comparing across angle conditions, participants assigned to the smaller angle conditions (less cost per look) looked more frequently compared to participants assigned to the larger angle conditions (more cost per look), implying that participants chose to look more frequently when the cost of each looking movement was less. Participants assigned to the larger angle conditions (i.e., 135° and 180°) used more time to complete each trial compared to those assigned to the smaller angle conditions (i.e., 45° and 90°). But across all angle conditions, participants used less time to complete each trial while continuing to perform the task accurately, indicating increased efficiency over the course of the 16 trials.

*Figure 2.* Summaries of model predictions for the dependent variables (top to bottom: number of looks, trial duration, eye, head, and body rotations) over trials (x-axis) across angle (separate colored lines) in Experiment 1. Shaded areas represent 95% confidence intervals.



We confirmed these results using a LMM predicting the number of looks, which showed significant main effects of trial and angle (Table 1). Participants decreased model looks over trials. In addition, participants looked less frequently when the models were at larger angles. Follow-up pairwise comparisons (Table S1 in supplementary material) showed a greater number of looks for 45° compared to 90°, 135°, and 180° ( $p < .001$ ). There was no significant difference between 90°, 135°, and 180°.

The results of a LMM predicting trial duration confirmed significant main effects of trial and angle, and the interaction between trial and angle (Table 1). Over trials, participants used less time to complete each trial but to different extents across angles, resulting in the interaction (Table S2 in supplementary material). The decrease rate over trial for 90° was significantly smaller than 180° ( $p = .03$ ). Follow-up pairwise comparisons (Table S1) on the main effect of angle showed that the trial duration was shorter at 45° and 90° compared to 135° and 180° ( $p < .01$ ). There was no significant difference between 45° and 90° or between 135° and 180°.

Table 1

*Summary of LMM results predicting number of look, trial duration, eye, head, and body rotations from trial and angle in Experiment 1.*

	Number of Looks				Trial Duration						
	<i>df</i>	<i>F</i>	<i>p</i>		<i>F</i>	<i>p</i>					
Trial	1	113.53	<.001	***	78.67	<.001	***				
Angle	3	23.82	<.001	***	10.32	<.001	***				
Trial × Angle	3	2.54	.056	n.s.	2.81	.039	*				

	Eye Rotation			Head Rotation			Body Rotation			
	<i>df</i>	<i>F</i>	<i>p</i>	<i>F</i>	<i>p</i>		<i>F</i>	<i>p</i>		
Trial	1	2.36	.125	n.s.	13.89	<.001	***	9.36	.002	**
Angle	3	8.06	<.001	***	29.70	<.001	***	48.50	<.001	***
Trial × Angle	3	.19	.901	n.s.	.89	.445	n.s.	.19	.901	n.s.

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

**Head and Body Rotations Changed with Practice.** Regarding eye-head-body movements, as Figure 2 C-E shows, eye rotations did not significantly change over trials in any of the angle conditions; head rotation increased significantly over trials for all angles; body rotation decreased significantly over trials for all angles. This implied that participants adjusted their eye-head-body coordination after repeated practice. They increased head rotation to lessen body rotation, reducing energy expenditure.

Each of these results was supported by a LMM testing eye, head, and body rotation as the DV (Table 1). The results of the LMM predicting eye rotation confirmed a significant main effect of angle. Follow-up pairwise comparisons (Table S1) on the main effect of angle showed that eye rotation was smaller at  $45^\circ$  than at  $90^\circ$ ,  $135^\circ$ , and  $180^\circ$  ( $p < .01$ ). There was no significant difference between  $90^\circ$ ,  $135^\circ$  and  $180^\circ$  (i.e.,  $45^\circ < 90^\circ = 135^\circ = 180^\circ$ ). The results of the LMM predicting head rotation confirmed significant main effects of trial and angle. Head rotation increased over trials for all

angles (Table S3 in supplementary material). Follow-up pairwise comparisons (Table S1) on the main effect of angle showed that overall head rotation increased as angle increased, except that there was no significant difference between  $135^\circ$  and  $180^\circ$  (i.e.,  $45^\circ < 90^\circ < 135^\circ = 180^\circ$ ). The results of the LMM predicting body rotation confirmed significant main effects of trial and angle. Body rotation decreased over trials for all angles (Table S3). Follow-up pairwise comparisons (Table S1) on the main effect of angle showed that overall body rotation increased as angle increased (i.e.,  $45^\circ < 90^\circ < 135^\circ < 180^\circ$ ).

### **Experiment 1 Discussion**

Experiment 1 investigated the effect of practice on information-gathering strategy and eye-head-body movements. The findings showed that participants looked less frequently at the models and increased head rotation to reduce body rotation over the course of 16 trials. It implied that they adjusted to less effortful strategy after practice. Also, participants used less time to complete the task after practice, indicating improved efficiency.

However, the results indicated that even after 16 practice trials participants still looked at the  $45^\circ$  models more frequently than needed. Specifically, the mean number of looks for the small angle in the trial 16 was 11, greater than the number of items (i.e., 8) in each model. In other words, participants could potentially copy them one by one—in which case they only needed to look at the model 8 times. But they kept checking the positions of items visually back and forth. It is possible that participants might not adopt the most efficient strategy spontaneously. Thus, Experiment 2 examined how people might spontaneously change their strategy for higher efficiency after being exposed to different strategies.

### **Experiment 2: Exposure to New Strategies**

#### **Method**

**Design and Participants.** This study used a mixed design. The between-subject factor was the angle at which the model was positioned ( $45^\circ$  or  $135^\circ$ ). The within-subject factor was block (i.e. pre-restriction, restriction, post-restriction).

Participants were alternately assigned to one of the angles ( $45^\circ$  or  $135^\circ$ ) and copied the models positioned at the assigned angle on the dominant-hand side for three blocks of 10 trials (30 trials in total).

Fifty college students were recruited from introductory psychology classes at the University of California, Riverside and received course credit for their participation. 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 chose not to report,  $M$  age = 19.21 years,  $SD$  age = 1.47), 17 for the angle of  $45^\circ$  and 16 for  $135^\circ$ . 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, eight 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  $45^\circ$  and 11 at  $135^\circ$ .

**Apparatus.** The experimental setup was the same as in Experiment 1. However, besides a mobile eye tracker and motion sensors, in the restriction block, participants wore a neck brace (right image in Figure 1B). The Aspen Collar neck brace (dimension: 26.7 x 24.1 x 1.8 cm, 159.0 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). The adjustable straps were tightened for a custom fit for each participant.

**Procedure.** The procedure was the same as in Experiment 1 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 movement while copying the models.

**Data Processing and Analyses.** Data synchronization and coding were conducted as in Experiment 1. The inter-rater reliability was high (98.8% agreement).

Similar analyses were performed as in Experiment 1. All data and analysis code are available on OSF ([https://osf.io/wdx73/?view\\_only=9524023bd92b41dbaae79e9b1ead0bf3](https://osf.io/wdx73/?view_only=9524023bd92b41dbaae79e9b1ead0bf3)). Five 2-way LMMs were applied to test the effects of block and angle on DVs (i.e., number of looks, trial duration, eye, head, and body rotations) separately. Block and angle 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  $\sim$  block  $\times$  angle + (1 | participant).

## Results

**Movement Restriction Induced Strategy Change.** To examine strategy change and efficiency, we compared the differences in DVs between the pre-restriction and restriction blocks, and between the pre-restriction and post-restriction blocks for different angles. As Figure 3 A-B shows, participants changed to a less effortful strategy to copy the model when head movement was restricted, and they continued to use the strategy after head restriction was removed. Also, participants further improved task efficiency (less time to complete the task) after removing the restriction although the number of looks were similar as with the head restriction. Compared to 45°, participants used less effortful strategy (i.e., fewer number of looks) to complete the task than when the model was positioned at 135°. Descriptive statistics are shown in Table 2.

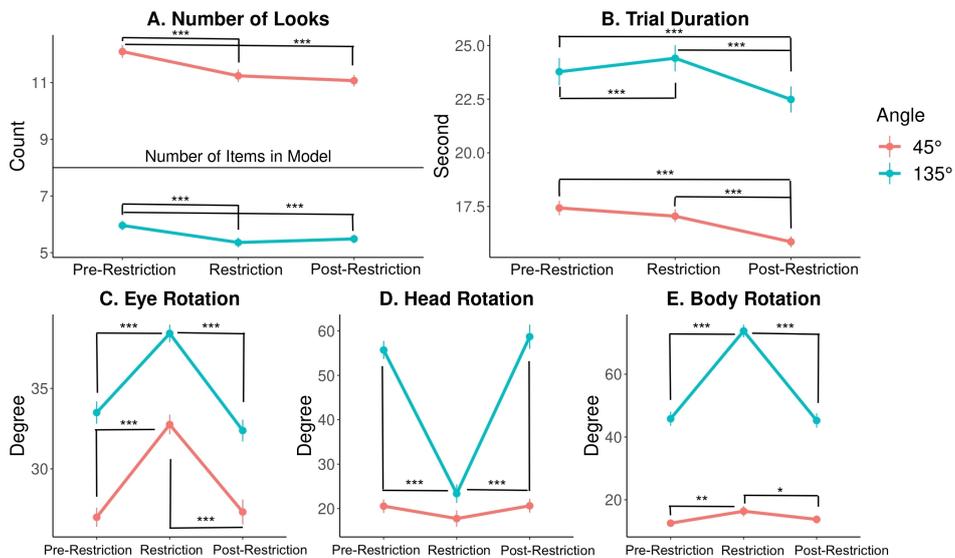
Table 3 shows model results to confirm the above findings. The results of the LMM predicting the number of looks showed significant main effects of block and angle (Table 3). Pairwise comparisons on the main effect of block (Table S4 in supplementary material) showed that the number of looks was greater for the pre-restriction block

Table 2

*Descriptive statistics (M and SD) for number of looks, trial duration, eye, head, and body rotations by block for each angle. Block 1, 2, and 3 are pre-restriction, restriction, and post-restriction blocks.*

Block	45°			135°		
	1	2	3	1	2	3
Number of Looks	12.09 (2.97)	11.24 (2.85)	11.07 (2.60)	5.96 (2.08)	5.36 (2.08)	5.49 (1.91)
Trial Duration	17.43 (4.36)	17.05 (4.16)	15.85 (3.26)	23.78 (7.92)	24.41 (7.47)	22.49 (7.52)
Eye Rotation	26.99 (7.05)	32.76 (7.15)	27.32 (9.02)	33.50 (7.28)	38.41 (5.68)	32.38 (7.02)
Head Rotation	20.55 (18.11)	17.75 (21.77)	20.63 (17.85)	55.70 (21.48)	23.37 (21.79)	58.70 (28.50)
Body Rotation	12.55 (13.82)	16.35 (19.41)	13.74 (14.76)	45.80 (23.64)	73.77 (20.98)	45.24 (23.88)

*Figure 3. Comparisons of number of looks, trial duration, eye, head, and body rotations across the blocks (x-axis) for different angles (separate colored lines).*



compared to the restriction and post-restriction blocks ( $p < .001$ ); but there was no significant difference between the restriction and post-restriction blocks (i.e., pre-restriction  $>$  restriction = post-restriction). In terms of angle effect, the number of looks was greater for  $45^\circ$  compared to  $135^\circ$  ( $p < .001$ ).

Table 3

*Summary of LMM results predicting number of looks, trial duration, eye, head, and body rotations from block and angle in Experiment 2.*

	Number of Looks				Trial Duration					
	<i>df</i>	<i>F</i>	<i>p</i>		<i>F</i>	<i>p</i>				
Block	2	13.88	<.001	***	34.56	<.001	***			
Angle	1	114.54	<.001	***	12.05	.002	**			
Block $\times$ Angle	2	1.84	.160	n.s.	6.65	.001	**			
	Eye Rotation				Head Rotation		Body Rotation			
	<i>df</i>	<i>F</i>	<i>p</i>		<i>F</i>	<i>p</i>		<i>F</i>	<i>p</i>	
Block	2	122.99	<.001	***	171.25	<.001	***	147.10	<.001	***
Angle	1	5.69	.026	*	11.51	.003	**	37.04	<.001	***
Block $\times$ Angle	2	1.29	.275	n.s.	139.68	<.001	***	79.34	<.001	***

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

The results of the LMM predicting trial duration showed significant main effects of block and angle, and the interaction between block and angle. Follow-up pairwise comparisons on the interaction (Table S5 in supplementary material) showed that for  $45^\circ$ , the trial duration was the lowest for the post-restriction block compared to the pre-restriction and restriction blocks ( $p < .001$ ); but there was no significant difference in the trial duration between the pre-restriction and restriction blocks (i.e., pre-restriction = restriction  $>$  post-restriction). For  $135^\circ$ , the trial duration was the lowest for the post-restriction block compared to the pre-restriction and restriction blocks ( $p < .001$ ); the trial duration for the restriction block was longer than the pre-restriction block ( $p < .001$ ) (i.e., restriction  $>$  pre-restriction  $>$  post-restriction).

**Eye-Head-Body Movements Coped with Restriction.** Regarding eye-head-body movements, as Figure 3 C-E 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. Each result was confirmed in a separate LMM testing eye rotation, head rotation, and body rotation as outcomes (Table 3).

The results of the LMM predicting eye rotation showed significant main effects of block and angle. Follow-up pairwise comparisons on the main effect of block (Table S4) showed that eye rotation was greater in the restriction block compared to pre-restriction and post-restriction blocks ( $p < .001$ ). But there was no significant difference between pre- and post-restriction blocks (i.e., restriction  $>$  pre-restriction = post-restriction). In terms of the main effect of angle, eye rotation was smaller at 45° compared to 135° regardless of block ( $p < .05$ ).

The results of the LMM predicting head rotation showed significant main effects of block and angle, and the interaction between block and angle. Follow-up pairwise comparisons on the interaction effect (Table S5) showed that for 45°, there was no significant difference in head rotation across block (i.e., pre-restriction = restriction = post-restriction). However, for 135°, head rotation was smaller during the restriction block compared to the pre-restriction and post-restriction blocks ( $p < .001$ ). But there was no significant difference between pre- and post-restriction blocks (i.e., restriction  $<$  pre-restriction = post-restriction).

The results of the LMM predicting body rotation showed significant main effects of block and angle, and the interaction between block and angle. Follow-up pairwise comparisons on the interaction effect (Table S5) showed that body rotation was greater in the restriction block compared to pre- and post-restriction blocks for both 45° and 135°. There was no significant difference between pre- and post-restriction (i.e., restriction  $>$  pre-restriction = post-restriction). But the differences in body rotation before and after head restriction were smaller for 45° than 135°, resulting in the interaction effect.

## **Experiment 2 Discussion**

Experiment 2 investigated whether exposing people to a different strategy led to higher efficiency. We restricted participants' head movement by having them wear a neck brace and investigated if the head restriction led participants to discover a more efficient strategy. Results showed that the increased motor cost caused by the head restriction led people to decrease number of looks, and the effect carried over to the post-restriction block—participants continued to use the less effortful strategy and improve efficiency (decreased trial duration) after removing the head restriction.

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 in Experiment 1. The carry-over effect of strategy exposure observed in Experiment 2 might be due to mere practice, not the result of head restriction.

Regarding eye-head-body movements, participants changed how they coordinated their eyes, head, and body while wearing a neck brace but resumed the original coordination after the head restriction was removed. This suggests that people's eye-head-body movements were independent of their strategy choice.

## **General Discussion**

The current study investigated how people adjust their eye-head-body movements to gather visual information and become efficient after repeated practice and strategy exposure. Experiment 1 found that participants changed their strategy by decreasing the number of looks and by making more efficient eye-head-body movements to gather information after repeated practice. Similarly, Experiment 2 showed participants chose a less effortful strategy after coping with head restriction that induced a strategy change.

### **Strategy Change and Efficiency**

A novel contribution of the current studies is showing how the information-gathering strategy 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 information-gathering strategy trial-by-trial while practicing the task, despite there being no time pressure or reward to motivate participants to improve. This suggests that people spontaneously adjust their strategy to save energy. Moreover, the current studies showed that people learn and adopt more efficient strategies after being exposed to different strategies. By fine-tuning their information-gathering strategies, people can better adapt to changing environmental parameters.

Despite improvements over trials, some aspects of participants' behavior might not have been optimal. For example, the current study found that participants looked at the model at 45° 11 times on average to copy a model consisting of 8 items. In contrast, participants looked at the same set of model 5 times when positioned at a larger angle. Even if participants copied the model in the most straightforward way—copying one item at a time, eight model looks would be sufficient. Although each model look at a small angle incurred low effort, by looking to the model frequently, participants expended unnecessary effort over the course of each trial. The similar strategy was observed in previous studies showing people tend to rely on motor effort to complete tasks (Ballard et al., 1995; Draschkow et al., 2021; Gray, Sims, Fu, & Schoelles, 2006; Inamdar & Pomplun, 2003; Lagers-van Haselen, van der Steen, & Frens, 2000; Luo & Franchak, 2022; Qing, Strauch, Van Maanen, & Van der Stigchel, 2024). Our results in the two current experiments replicated that participants were consistent in the over-expenditure of motor effort, and that over-expenditure persists even after repeated practice or when the head was restricted.

Why did people consistently expend more motor effort than necessary despite multiple degrees of freedom in how they could gather visual information? It is possible that compared to motor effort, the use of cognitive resources (e.g., holding information in working memory) may be weighted as more expensive and/or aversive (Bilda & Gero, 2007; Cowan, 2001; Hardt, Nader, & Nadel, 2013; Kvitelashvili & Kessler, 2024; Miller, 1956). Previous studies showed that people chose to walk for longer distance Hardiess, Basten, and Mallot (2011), or carry boxes (Feghhi, Franchak, & Rosenbaum, 2021;

Feghhi & Rosenbaum, 2019, 2021) rather than memorizing information. Some studies further explored how people compared the difficulty of physical and cognitive tasks (Feghhi et al., 2021; Feghhi & Rosenbaum, 2019, 2021; Janczyk, Feghhi, & Rosenbaum, 2022). When participants were required to carry a box through a gap and remember digits associated with the gap, participants treated memorizing an additional 0.55 digits as equivalent to the physical demand of walking through a narrower gap (36 cm) versus a wider gap (81 cm) (Feghhi & Rosenbaum, 2019). Moreover, a recent meta-analysis showed that exerting mental effort is associated with experiencing negative emotions (David et al., 2024). Future studies could investigate whether time constraints, reward, feedback, or the teaching of skills might lead people to use more cognitive resources rather than motor effort.

Note that the current study evaluated strategy efficiency based on physical effort (e.g., number of looks) and time. That is, expending less physical effort and using less time to complete the task were considered efficient. However, participants might choose strategies that avoid errors or minimize executive control (Janczyk et al., 2022). One way to approach the problem is to investigate the impact of metacognition in the task. Possibly, 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 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 (Howes et al., 2016), 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's awareness of strategy use would help them improve efficiency.

In addition, the current study focused on the physical aspect of people's information-gathering strategy such as how frequently people looked and how they coordinated their eyes, head, and body. Future studies should explore the cognitive aspect of information-gathering strategies. For example, how do people explore visual information while looking? What do they choose to remember each time (e.g., the color or position of one or more items)? How does the cognitive strategy affect their tendency to over-expend motor effort? Understanding the cognitive aspect of their strategies may give insights into the trade-off between physical and cognitive efforts.

### **Eye-Head-Body Movements**

Another contribution of the study was to capture the eye-head-body movements during the copying task. It allowed us to examine the motor effort of information gathering more accurately as the motor effort to look depends on how the eyes, head, and body are coordinated to shift gaze (Franchak, 2020a, 2020b; Franchak et al., 2021; Freedman & Sparks, 2000; Land, 2004; Sidenmark & Gellersen, 2019; Solomon, Vijay Kumar, Jenkins, & Jewell, 2006). Eye movements are quick and cost less energetically compared to head and body movements. However, Experiment 1 showed that to reduce the need for costly body movements when making small gaze shifts, participants gradually increased the magnitude of head movements rather than increasing the magnitude of lower-effort eye movement. It may imply that compared to the head, people tend to keep the eyes centered (Burlingham, Sendhilnathan, Komogortsev, Murdison, & Proulx, 2023; Franchak et al., 2021).

Moreover, in Experiment 2, we directly altered how the eyes, head, and body coordinated by restricting head movements. Results showed that participants changed their eye-head-body coordination while wearing a neck brace, indicating a successful manipulation on the cost of head movement. Specifically, when the head was restricted by the neck brace, both the eyes and body increased their movements. However, 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 preferred. Importantly, this indicates that the strategy changes that participants made following head restriction could not be explained by how the eyes, head, and body coordinated—both improvements were likely adapted independently.

### **Conclusion**

In sum, the current study showed that people adjusted the way they moved their eyes, head, and body to gather visual information for higher efficiency after repeated practice and strategy exposure. Both practice and strategy exposure improved efficiency by changing to less effortful strategies and allowing participants to make visual exploratory movements more efficient. The findings enhanced our understanding of task learning and to what degree people optimize exploratory visual behavior.

### **Competing Interests**

The authors declare that they have no conflict of interest.

### **Data Availability**

Data and analysis code are available on Open Science Foundation ([https://osf.io/wdx73/?view\\_only=9524023bd92b41dbaee79e9b1ead0bf3](https://osf.io/wdx73/?view_only=9524023bd92b41dbaee79e9b1ead0bf3)).

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## Supplementary Material

Table S1: Pairwise comparisons between angle for number of look, trial duration, eye, head, and body rotations in Experiment 1.

	Number of Looks				Trial Duration					
	<i>df</i>	<i>t</i>	<i>p</i>		<i>t</i>	<i>p</i>				
45° vs 90°	44	5.58	<.001	***	-.33	.987	n.s.			
45° vs 135°	44	6.49	<.001	***	-3.36	.009	**			
45° vs 180°	44	7.57	<.001	***	-3.62	.004	**			
90° vs 135°	44	1.32	.554	n.s.	-3.39	.008	**			
90° vs 180°	44	2.25	.127	n.s.	-3.71	.003	**			
135° vs 180°	44	.79	.861	n.s.	-.09	.999	n.s.			
	Eye Rotation				Head Rotation		Body Rotation			
	<i>df</i>	<i>t</i>	<i>p</i>		<i>t</i>	<i>p</i>		<i>t</i>	<i>p</i>	
45° vs 90°	33	-4.21	.001	**	-3.36	.010	*	-2.83	.037	*
45° vs 135°	33	-4.49	<.001	***	-6.37	<.001	***	-7.04	<.001	***
45° vs 180°	33	-4.29	<.001	***	-8.70	<.001	***	-11.80	<.001	***
90° vs 135°	33	-.50	.959	n.s.	-3.32	.011	*	-4.55	<.001	***
90° vs 180°	33	-.41	.977	n.s.	-5.84	<.001	***	-9.60	<.001	***
135° vs 180°	33	.07	.999	n.s.	-2.51	.077	n.s.	-4.97	<.001	***

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

**Table S2: Pairwise comparisons of slopes between angle for trial duration in Experiment 1.**

	<i>df</i>	<i>t</i>	<i>p</i>	
45° vs 90°	707	-.55	.948	n.s.
45° vs 135°	707	.75	.877	n.s.
45° vs 180°	707	1.90	.229	n.s.
90° vs 135°	707	1.41	.496	n.s.
90° vs 180°	707	2.78	.028	*
135° vs 180°	707	1.15	.659	n.s.

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

**Table S3: The slopes of trial for number of look, trial duration, head, and body rotations in Experiment 1. Eye rotation is not included as the main effect of trial is not significant for eye rotation.**

	Number of Looks				Trial Duration		
	<i>df</i>	<i>trial trend</i>	<i>lower CL</i>	<i>upper CL</i>	<i>trial trend</i>	<i>lower CL</i>	<i>upper CL</i>
45°	707	-.21	-.27	-.15	-.23	-.37	-.09
90°	707	-.13	-.18	-.09	-.18	-.29	-.07
135°	707	-.11	-.17	-.06	-.30	-.43	-.17
180°	707	-.12	-.17	-.07	-.41	-.52	-.29
	Head Rotation			Body Rotation			
	<i>df</i>	<i>trial trend</i>	<i>lower CL</i>	<i>upper CL</i>	<i>trial trend</i>	<i>lower CL</i>	<i>upper CL</i>
45°	546	.26	.08	.45	-.28	-.56	.00
90°	546	.23	.07	.40	-.26	-.51	-.01
135°	546	.09	-.10	.27	-.20	-.48	.09
180°	546	.12	-.08	.30	-.14	-.44	.16

**Table S4: Pairwise comparisons between block for number of looks and eye rotation in Experiment 2. Block 1, 2 and 3 are pre-restriction, restriction, and post-restriction blocks.**

<i>Block</i>	Number of Looks				Eye Rotation			
	<i>df</i>	<i>t</i>	<i>p</i>		<i>df</i>	<i>t</i>	<i>p</i>	
1 vs 2	920	4.30	<.001	***	709	-13.12	<.001	***
1 vs 3	920	4.77	<.001	***	709	.99	.586	n.s.
2 vs 3	920	.46	.891	n.s.	709	14.01	<.001	***

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

**Table S5: Interaction effect between block and angle for trial duration, head, and body rotations in Experiment 2. Block 1, 2 and 3 are pre-restriction, restriction, and post-restriction blocks.**

<b>Trial Duration</b>		<b>45°</b>			<b>135°</b>		
<i>Block</i>	<i>df</i>	<i>t</i>	<i>p</i>		<i>t</i>	<i>p</i>	
1 vs 2	919	1.04	.299	n.s.	-3.91	<.001	***
1 vs 3	919	5.03	<.001	***	3.41	<.001	***
2 vs 3	919	3.98	<.001	***	7.29	<.001	***

<b>Head Rotation</b>		<b>45°</b>			<b>135°</b>		
<i>Block</i>	<i>df</i>	<i>t</i>	<i>p</i>		<i>t</i>	<i>p</i>	
1 vs 2	712	1.08	.653	n.s.	19.51	<.001	***
1 vs 3	712	-.16	.871	n.s.	-1.83	.068	n.s.
2 vs 3	712	-1.23	.653	n.s.	-21.33	<.001	***

<b>Body Rotation</b>		<b>45°</b>			<b>135°</b>		
<i>Block</i>	<i>df</i>	<i>t</i>	<i>p</i>		<i>t</i>	<i>p</i>	
1 vs 2	709	-3.44	.002	**	-17.06	<.001	***
1 vs 3	709	-.88	.380	n.s.	.44	.662	n.s.
2 vs 3	709	2.53	.023	*	17.42	<.001	***

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