Visuomotor Lag and the Intermanual Speed Advantage

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Previous research has found evidence for the Intermanual Speed Advantage (ISA), wherein novice actors perform a visually-guided, two-handed task faster with one hand from each partner (i.e., intermanually) compared to when one actor completes the task with their own two hands (i.e., bimanually). The ISA is erased, however, after the task has been well-practiced by both actors bimanually. Visuomotor coupling (i.e., coordination between eye and hand movements) has been found to account for the moderating effect of practice on the ISA. Through a lag analysis, this study uses secondary data to further investigate visuomotor coupling and the ISA. Findings show that the time lag between the gaze and the hands of novice actors entrains to the partner with lower visuomotor coupling (i.e., the less coupled partner) in the intermanual trials. However, for experienced actors with previous bimanual practice, dyads entrain to the more coupled partner.

INTRODUCTION

A robust effect reported in the interpersonal coordination literature is the Intermanual Speed Advantage (ISA). This speed advantage occurs when a visually-guided, two-handed task is completed faster when that task is conducted with one hand from two different people (i.e., intermanually), as opposed to two hands from the same person (i.e., bimanually). This "coordination mode effect" has been observed in novices in a variety of tasks: pursuit-rotor tracking (Reed et al., 2006); simulated laparoscopic cutting (Crites & Gorman, 2017, 2018; Zheng et al., 2005); and teleoperation (Gorman & Crites, 2013). Furthermore, recent investigations have shown the reversal or elimination of the ISA when the task is well-practiced by individual members of the dyad (Crites & Gorman 2017, 2018; Gorman & Crites, 2015; Zheng et al., 2005).

The effect of practice on the ISA was explored in a series of studies by Crites (2018) where, in addition to replicating the effects of practice in a novel simulated laparoscopic cutting task, he identified underlying behavioral factors that accounted for the presence of the ISA in novice actors. Differences between novice and practiced actors in these studies revealed that manual and visuomotor coordination constraints accounted for the presence of the ISA in novices. Specifically, the fluency with which practiced actors were able to coordinate their limbs enabled them to make more simultaneous movements across both hands, allowing bimanual trials to be completed as quickly as intermanual trials. Novices' bimanual actions were more sequential, which slowed down bimanual execution and resulted in faster intermanual trials for this group. The present study builds on this work to assess how visuomotor coordination is influenced by both bimanual practice and the joint action of a dyad. The cross-recurrence method used to investigate manual coupling in Crites and Gorman's (2017) work is adapted here to now explore visuomotor coupling.

The present study investigates visuomotor coupling within and between individuals as they complete a visually-guided two-handed task. Coupling is generally defined as interaction between systems during the course of an action or a series of actions (Gorman et al., 2017). In the context of the current study, the coupled systems are the motor and visual systems of the actor(s) completing the task. These systems' combined action then makes up the visuomotor system, which is investigated under the following definition of visuomotor coupling: "the sequential, spatial, and temporal eye-hand dependencies that take place during manual coordination" (Crites & Gorman, 2018, p. 1311). Visuomotor coupling is a particular hindrance to novice actors who rely heavily on gaze to direct and monitor motor actions. This visual dependency is especially detrimental in bimanual coordination, as there are two hands acting and only one line of sight to guide them (Sailer et al., 2005). In part, this explains why novices perform better in the intermanual coordination mode, such that the time-sharing requirement of the gaze across the two hands is negated (Crites & Gorman, 2018).

Visuomotor *de*coupling (i.e., the increased independence of manual actions from the direction of the gaze) is advantageous when completing a bimanual task that relies on the coordination of simultaneous movements of the two hands. One mechanism for decoupling is bimanual practice, such that tasks become less visually-guided as performance improves (Sailer et al., 2005). This finding helps account for the moderating effect of practice on the ISA. A reduction in visual reliance (i.e., visuomotor decoupling) via practice allows actors in the bimanual condition to perform as well as those in the intermanual condition (Crites, 2018). The present study assesses visuomotor coupling behavior in the context of this practice effect.

The purpose of the present study is to understand how both bimanual practice and the different coordination modes affect the dependent relationship between the visual and motor systems in two-handed tasks. Visuomotor coupling is investigated using a characteristic lag analysis, which examines how the time lag between the position of the gaze and position of the hands changes as a function of practice and coordination mode. Coupling is operationally defined as shorter lag values (i.e., the gaze and hands follow each other closely). Decoupling is operationally defined as longer lag values, wherein the gaze and hands are relatively far apart in time and space. This lag analysis utilizes data collected for the purposes of prior studies reported by Crites (2018).

Hypotheses

In investigations into visually-coupled intermanual oscillatory coordination, Oullier and colleagues (2008) proposed two alternatives to how individuals would become synchronized when interacting with each other. The first alternative proposed that both individuals would spontaneously forego their natural oscillation frequency (up-down finger oscillations) for a unique interpersonal frequency brought on by visually coupling with each other's movements (i.e., emergence). The second alternative suggested that one partner would spontaneously forgo their preferred oscillation frequency for that of their partner (i.e., entrainment to one partner). These alternatives are investigated in the present study. It is hypothesized that novices assume an emergent relationship in the intermanual condition, such that the visuomotor lag values observed in the intermanual condition are longer than those of either participant when acting alone in the intermanual condition (Hypothesis 1). This would suggest a further decoupling in the intermanual condition and explain why the ISA is present in novices, such that decoupling is advantageous in manual tasks. Alternatively, practiced actors will entrain to the coordination pattern established by the member of the dyad with the longer visuomotor lag value in the bimanual condition (Hypothesis 2). This places a ceiling on coordination in the intermanual condition such that they are not able to decouple further. This inability to further decouple could then explain the disappearance of the ISA in practiced actors.

METHOD

Participants

Twenty-four Georgia Tech undergraduate students were recruited for Experiment 1 (E1). Their average age was 20.71 (SD = 2.28) and the sample was 21% female. Another 24 students—a separate sample from E1—were recruited for Experiment 2 (E2). The E2 sample had an average age of 23.58 (SD = 4.30) and was 50% female. Due to an equipment failure, seven dyads (14 participants) were excluded from E2 analyses. All participants were right-handed.

Experimental Design

To investigate the presence of the ISA, Crites (2018) manipulated the within-subjects variable Coordination Mode, which had two levels: Bimanual and Intermanual. In the Bimanual condition, individuals completed the simulated cutting task with both of their hands. In the Intermanual condition, dyads completed the task with the right hand of one partner and the left hand of the other partner. The order of Coordination Mode was counterbalanced. Here, we use this manipulated variable to define three levels of the measured variable Coordination Pattern: Bi_Longer, Bi_Shorter and Inter. Inter corresponds to dyads acting in the intermanual condition. Bi_Longer corresponds to the participant in the dyad with the longer average visuomotor lag, while Bi_Shorter corresponds to the participant with the shorter average visuomotor lag. Parsing the bimanual trials in this way allowed for the comparisons needed to test the hypotheses.

The data were also separated based on two levels of Practice: Novice and Practiced. Participants in E1 were considered Novice, as they had limited experience with the task before engaging in the experimental trials. Those in E2 were considered Practiced, as they had two days of bimanual practice with the task, wherein across the two days the individual participants completed 200 total trials to reach a performance asymptote. On the third day, experimental trials began. The present study assessed this day-three data from E2 and the experimental trials from E1.

Hypotheses were tested using one-way between-subjects ANOVAs for each experiment, wherein Coordination Pattern was assessed as the independent variable. Planned comparisons assess differences between Bi_Longer and Inter, and Bi_Shorter and Inter to test the two hypotheses. Specifically, we hypothesize lag from Inter trials to be longer than both Bi_Shorter and Bi_Longer trials in the novice participants from E1. However, for those experienced actors in E2, we hypothesize Inter lag to be longer than only the Bi_Shorter trials, but roughly equivalent to Bi_Longer trials.

Apparatus

Crites built an apparatus to ensure the interactive task would be completed faster with the simultaneous actions of both hands working at the same time (see Figure 1 from Crites & Gorman, 2018). Participants wore Dikablis Eye-Tracking Glasses to capture their gaze patterns with two eye-facing binocular cameras. The location of their hands was also recorded from these glasses with an outward facing scene camera (Ergoneers, 2014).

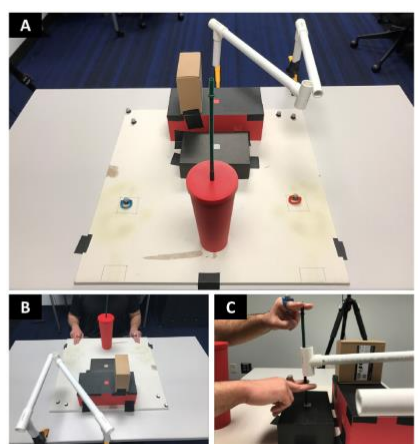

Figure 1. From Crites & Gorman (2018). (A) The apparatus from the participant's view. (B) A participant in the starting position of a bimanual trial and (C) completing the task.

Task Overview

Previous research that observed the ISA employed tasks that shared the following attributes, which were implemented in the Crites & Gorman (2017, 2018) task. The task was designed to be interactive across the hands, such that one or more subtasks were dependent on action from both hands. The task also needed to be agonistic, meaning using two hands to complete the subtasks would be advantageous, over just using one hand (Jarrassé et al., 2012). Furthermore, the task was designed to exploit behavioral factors that contribute to the speed advantage: it was visually-guided and relied on asymmetric movement of the limbs (Crites & Gorman, 2017, 2018).

The task had two component parts, each enacted by one of the opposing hands. In every trial, the index and middle fingers of the right hand served as the “scissor tool”, and those of the left hand served as the “grasper tool.” Fingers were used instead of actual tools to allow for a more direct assessment of the motor system (Crites, 2018). Generally, participants were required to move a straw-like object and a pipe from their starting locations and insert the straw through the pipe. Then they “cut” the straw before returning both items to their starting locations. These items can be seen in Figure 2. The task could be assessed as six discrete subtasks for each hand (i.e., for both the grasper and the scissor). The identified subtasks provided clear start and end points for each motion and fixation and corresponded to six discrete Areas of Interest (AOIs) on the task apparatus for each tool.

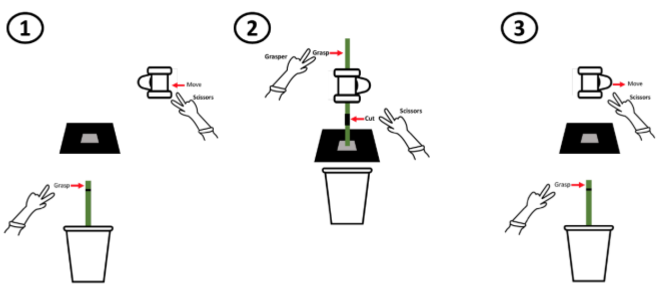

Figure 2. A representation of the task requirements from Crites & Gorman (2017, 2018).

Measures

The present study utilizes timestamp data associated with data streams from both hands (“tools”). The timestamps correspond to the start and end times of the gaze and hands as they move in and out of the AOIs. In a procedure similar to Richardson & Dale (2005), these timestamp data points were converted into symbolic 1 Hz time series for each tool and each modality, resulting in four time series per trial: Eye_Grasper; Hand_Grasper; Eye_Scissor; Hand_Scissor. Nominal codes were assigned to the AOIs, wherein, when the gaze landed within an AOI for the grasper tool, the Eye_Grasper time series would denote the code of that AOI. When the eyes were not in an AOI, the Eye_Grasper time series would denote a code of 0. This process was repeated for the other three time series.

Using the time series for each tool (one from the gaze and one from the hands), two characteristic lag values—one for each tool—were generated per trial using the *crqa* R-package (Coco & Dale, 2012). Characteristic lag is a metric extracted from a Cross-Recurrence Plot (CRP), wherein the two time series are plotted against one another. The CRP graphically represents when the two systems—the gaze and the hands—are in the same location. A simplified CRP is shown in Figure 3. A recurrence point is plotted when the nominal code of one system (e.g., Eye_Grasper AOI) equals that of the other (e.g., Hand_Grasper AOI). Along the main diagonal of a CRP, the two systems are aligned as they were in real time. Diagonals off the main diagonal represent different time lags, such that the diagonals directly neighboring the main diagonal lag one system behind the other by 1 Hz. The lag metric is determined based on which diagonal has the highest percentage of recurrence points. This metric represents the time lag at which one system followed behind the other (Richardson & Dale, 2005).

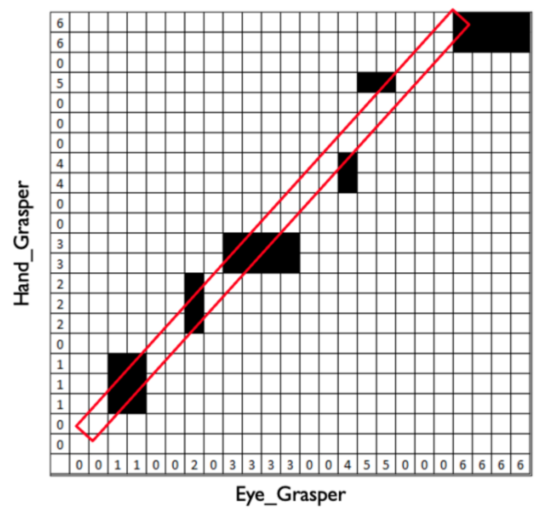

Figure 3. A simplified CRP from the present study. Recurrence points are “filled in” when the two systems align. The characteristic lag for this system would fall one diagonal off the main diagonal, as shown in red.

Procedure

After obtaining informed consent, participants were shown the apparatus and given an overview of the different coordination modes. Participants were not allowed to speak to each other at any point. Participants were instructed to complete the task “as quickly and accurately as possible”. In E1, before beginning the experimental trials, participants completed a short series of practice trials in both coordination modes. In E2, a separate group of participants from E1, completed the 200 bimanual practice trails across two days before returning to the lab for the experimental trails on the third day. For each dyad across the two experiments, 30 experimental trials were completed: 10 for each participant in the bimanual mode and 10 for the dyad in the intermanual mode.

RESULTS

Lag values between the Scissor and Grasper tools were uncorrelated (Experiment 1: r = -0.08, p = 0.40; Experiment 2: r = 0.24, p = 0.11). Thus, it was not appropriate to average eye-hand lag values across the two tools for each trial. Analyses proceeded separately for the two tools, resulting in four one-way between subject ANOVAs: two for E1 (visuomotor coupling for grasper and for scissors) and two for E2 (visuomotor coupling for grasper and for scissors). Four outliers (+3 SD) were removed from analyses—two from E1 and two from E2.

Hypothesis 1: Novice Actors

H1 stated that novices acting in the intermanual condition (Inter) would be further decoupled (i.e., have longer lag values) than both novice individuals acting in the bimanual condition (Bi_Longer and Bi_Shorter). This was to suggest an emergent visuomotor coupling pattern brought on by the interaction. For the analysis of the Grasper lag values in Experiment 1, there was a significant effect, $F(2, 100) = 8.09$, $p = .001$, $\eta^2 = 0.14$. Results from planned comparisons show Bi_Shorter ($M = -120.42$, $SD = 84.47$) was significantly shorter than Inter ($M = -206.68$, $SD = 115.76$), which was in agreement with predictions that Bi_Shorter would have a shorter lag than the Inter condition, $p = .001$. Bi_Longer was also predicted to have a shorter lag than Inter, however, the Bi_Longer ($M = -214.09$, $SD = 122.94$) and Inter conditions did not significantly differ, $p = .78$. Though not implicated in the hypotheses, the Bi_Shorter and Bi_Longer conditions also significantly differed, $p = .001$. For the Scissor values, there was not a significant effect, $F(2, 101) = 2.90$, $p = .06$, $\eta^2 = 0.05$, although the pattern of results was similar (Figure 4).

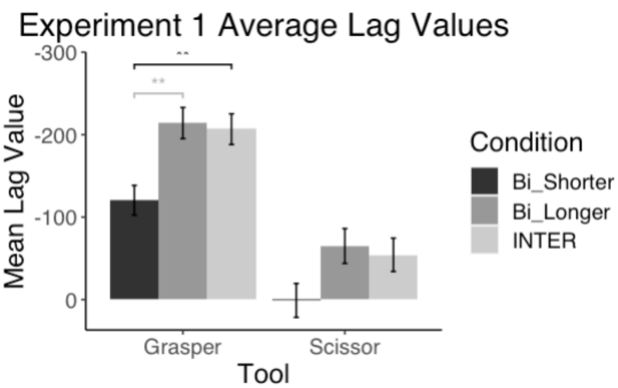

Figure 4. Mean lag values for both tools across the conditions of Coordination Pattern for E1. Bars note standard error.

Hypothesis 2: Practiced Actors

H2 stated that the coordination pattern of practiced actors in the intermanual condition (Inter) would resemble the coordination pattern of the bimanual actor with the longer visuomotor lag value (Bi_Longer). The bimanual actor with the shorter lag value (Bi_Shorter) would be shorter than the lag values of both Bi_Longer and Inter. This was to suggest the coordination pattern of the dyad would entrain to the coordination pattern of the Bi_Longer participant, such that the dyad would not be able to further decouple in the intermanual condition; and thus, not be able to perform the task faster as a pair. For the analysis of the Grasper lag value in Experiment 2, there was a significant effect, $F(2, 40) = 5.37$, $p = .01$, $\eta^2 = 0.21$. The lag values of Bi_Longer ($M = -165.36$, $SD = 58.58$) were significantly longer than Inter ($M = -95.21$, $SD = 90.95$), which contradicted the hypothesis that Bi_Longer and Inter would not differ, $p = .02$. Bi_Shorter ($M = -72.67$, $SD = 85.40$) did not significantly differ from Inter, which contradicted the prediction that the lag of the Inter condition would be longer than Bi_Shorter, $p = .51$. Though not implicated in the hypotheses, Bi_Shorter and Bi_Longer also significantly differed, $p = .003$. For the analysis of the Scissor lag values, there was a not significant effect, $F(2, 41) = 2.286$, $p = .12$, $\eta^2 = 0.10$. See Figure 5 for the results of both tools.

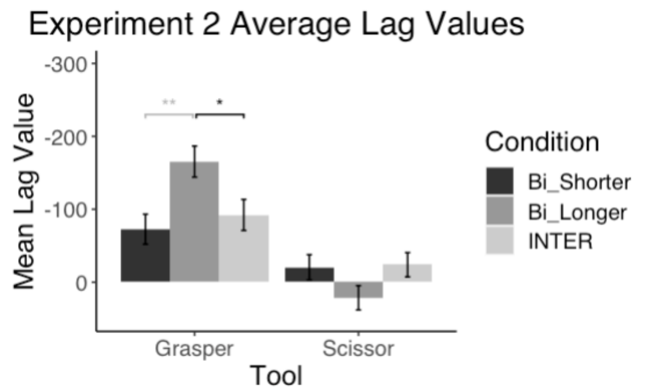

Figure 5. Mean lag values for both tools across the conditions of Coordination Pattern for E2. Bars note standard error.

DISCUSSION

The motivation for this analysis was to understand whether unique lag in the eye and hand relationship is an underlying factor that contributes to the erasure of the ISA after actors have had previous bimanual practice. Broadly, this work relates to an underlying mechanism of human interaction and interpersonal coordination. Though the original hypotheses were generally not supported by our findings, these results can be understood as two different entrainment patterns. For Experiment 1, we see the dyad entrain to the more decoupled partner; the intermanual trials have a similar lag to the Bi_Longer trials. This finding provides support for how coupling underlies the ISA, such that more *de*coupling (i.e., longer lag values) in the intermanual coordination of unpracticed dyads is associated with faster performance when compared to bimanual execution (Crites, 2018). These results suggest that one mechanism for establishing a less coupled pattern of execution in intermanual coordination is for the dyad to assume the previously established visuomotor coordination pattern of the more decoupled partner.

In Experiment 2, we also see entrainment; however here, the dyad entrains to the more coupled partner, where the intermanual lag values are similar to the Bi_Shorter trials. These results suggests that there is tighter visuomotor coupling in intermanual trials for practiced dyads compared to unpracticed dyads, as shown in Figure 6. This finding is reflected in Crites' (2018) results, as well. He observed that the hands and gaze could proceed closer in step after the task had been practiced with no cost to speed. Because the task had been so well practiced, actors required less input from the gaze to coordinate manual action (Crites, 2018). This is similarly observed in the results of the present study where the two modalities are more coupled in E2 results, but speed of execution is still superior to E1 trials times, as shown in Crites (2018). Following Crites' conclusion that visuomotor coupling increases with practice, the decrease in lag values across the two experiments provides support for operationalizing visuomotor coupling using a lag metric, as done here.

Figure 6. Mean lag values from the Grasper tool for both experiments. Coupling increased from E1 to E2.

Conclusion

The present study adopted a novel approach to operationalizing visuomotor coordination. Past work has employed the lag metric to assess gaze patterns (Richardson & Dale, 2005), facial expressions, and communication patterns of interlocutors (Louwerse et al., 2012), however those earlier studies did not investigate cross-modality effects, as done here. There are some parallels to be made from conclusions drawn from lag analyses that assessed communication data to the present study involving motor skills. Richardson and Dale (2005) showed that the more closely a listener's eye fixations followed a speaker's, the higher the listener scored on a comprehension test. It is possible a similar dynamic is established in the present task with visuomotor coordination, wherein with skill acquisition, the visual and motor systems track closer in step to each other. These findings may suggest a similar dynamic occurs between cognitive and behavioral mechanisms of comprehension and skill acquisition.

This work also extends the interpersonal motor coordination literature, which historically has been assessed in simple coupled oscillator tasks. While Oullier and colleagues (2008) observed an emergent pattern of coordination brought on by the interaction in a simple finger tapping task, with the more complex task investigated here, entrainment appears to be the dominant interactive mechanism. Still more work is needed to understand how interpersonal coordination is best managed in complex manual tasks.

Ultimately, this work adds to our understanding of how novices versus experienced operators interact with a manual task, and how that interaction is influenced by the addition of a partner. Results may implicate entrainment training paradigms used for such domains as laparoscopic surgery and teleoperation, wherein the work environments frequently require intermanual coordination.

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REFERENCES

Coco, M. I., & Dale, R. (2014). Cross-recurrence quantification analysis of categorical and continuous time series: an R package. *Frontiers in psychology*, 5, 510.

Crites, M. J. (2018). *Speed Differences during Two-Handed Tasks: Bimanual versus Intermanual Coordination and the Effect of Practice* [Doctoral dissertation]. Texas Tech University.

Crites, M. J., & Gorman, J. C. (2017, September). Bimanual coupling and the intermanual speed advantage. In *Proceedings of the Human Factors and Ergonomics Society Annual Meeting* (Vol. 61, No. 1, pp. 1385-1389). Sage CA: Los Angeles, CA: SAGE Publications.

Crites, M. J., & Gorman, J. C. (2018, September). Visuomotor Coupling during Two-Handed Tasks: An Investigation of Bimanual and Intermanual Coordination. In *Proceedings of the Human Factors and Ergonomics Society Annual Meeting* (Vol. 62, No. 1, pp. 1311-1315). Sage CA: Los Angeles, CA: SAGE Publications.

Ergoneers (2015). Dikablis Glasses. http://www.ergoneers.com/en/hardware/eyetracking/.

Gorman, J. C., Dunbar, T. A., Grimm, D., & Gipson, C. L. (2017). Understanding and modeling teams as dynamical systems. *Frontiers in psychology*, 8, 1053.

Gorman, J. C., & Crites, M. J. (2013). Are two hands (from different people) better than one? Mode effects and differential transfer between manual coordination modes. *Human Factors*, *55*, 815-829.

Gorman, J. C., & Crites, M. J. (2015). Learning to tie well with others: bimanual versus intermanual performance of a highly practised skill. *Ergonomics*, 58, 680-697.

Jarrassé, N., Charalambous, T., & Burdet, E. (2012). A framework to describe, analyze and generate interactive motor behaviors. *PloS one*, *7*(11), e49945.

Louwerse, M. M., Dale, R., Bard, E. G., & Jeuniaux, P. (2012). Behavior matching in multimodal communication is synchronized. *Cognitive science*, *36*(8), 1404-1426.

Oullier, O., De Guzman, G. C., Jantzen, K. J., Lagarde, J., & Scott Kelso, J. A. (2008). Social coordination dynamics: Measuring human bonding. *Social neuroscience*, *3*(2), 178-192.

Reed, K., Peshkin, M., Hartmann, M. J., Grabowecky, M., Patton, J., & Vishton, P. M. (2006). Haptically linked dyads: are two motor-control systems better than one?. *Psychological science*.

Richardson, D. C., & Dale, R. (2005). Looking to understand: The coupling between speakers' and listeners' eye movements and its relationship to discourse comprehension. *Cognitive science*, *29*(6), 1045-1060.

Sailer, U., Flanagan, J. R., & Johansson, R. S. (2005). Eye–hand coordination during learning of a novel visuomotor task. *Journal of Neuroscience*, *25*(39), 8833-8842.

Zheng, B., Verjee, F., Lomax, A., & MacKenzie, C. L. (2005). Video analysis of endoscopic cutting task performed by one versus two operators. *Surgical Endoscopy and Other Interventional Techniques*, *19*(10), 1388-1395.