Summer 2016

Measuring Team Collaboration and Effects of Target Guidance in a Visual Search Task

Christopher Morley
Old Dominion University

MEASURING TEAM COLLABORATION AND EFFECTS OF TARGET GUIDANCE IN A VISUAL SEARCH TASK

Christopher Morley
B.S. May 2013, State University of New York, College at Oneonta

A Thesis Submitted to the Faculty of
Old Dominion University in Partial Fulfillment of the
Requirements for the Degree of

MASTER OF SCIENCE

PSYCHOLOGY

OLD DOMINION UNIVERSITY
August 2016

Approved by:

Yusuke Yamani (Director)

Christopher Brill (Member)

Philip Langlais (Member)

ABSTRACT

MEASURING TEAM COLLABORATION AND EFFECTS OF TARGET GUIDANCE IN A VISUAL SEARCH TASK

Christopher Morley
Old Dominion University, 2016
Director: Dr. Yusuke Yamani

Many professional tasks, including military operations and medical operations, involve a team of operators searching for a target on a common visual display. Previous works on collaborative visual search employed analysis of mean response time (RT) and error rates, which may not offer direct measurement of the capacity of a team nor changes in performance across task time. *Workload capacity,* indexed by the capacity coefficient, *C(t),* measures performance efficiency for cognitive systems with multiple and concurrent information-processing channels (Townsend & Nozawa, 1995). The current study applied a workload capacity analysis to quantify performance efficiency of pairs of participants in a difficult visual search task. Sixty-eight participants performed a speeded visual search task both solitarily and in pairs with varying levels of target guidance. Each search display contained a target (O) and non-targets (Cs) where the gaps of either 20% (low target guidance) or 80% (high target guidance) of non-targets predicted the location of the target. Results indicate that solitary participants exhibited significantly faster RT in the high guidance condition than the low guidance condition, whereas paired participants demonstrated no difference in RT across target guidance conditions. Additionally, paired participants exhibited limited capacity in both target guidance conditions, indicating that participants slowed response speeds when working collaboratively compared to solitarily, regardless of levels of target guidance. Providing target guidance information may not

prevent operators from slowing individual response speeds in collaborative trials. Present findings have implications for the effectiveness of providing target guidance to speed operator responses in contexts such as, search and rescue, surveillance, and reconnaissance.

This thesis is dedicated to Ian, Guy, Joe, and Brendan.

ACKNOWLEDGEMENTS

I would like to thank my advisor, Dr. Yusuke Yamani, for his constant support throughout my graduate studies, and my committee members, Dr. Christopher Brill and Dr. Philip Langlais, for their assistance on this research project. Additionally, I wish to thank my cohort for their continued friendship and encouragement.

Finally, I would like to thank my family for their unconditional love and support, not only throughout this experience, but also throughout my life. My appreciation for you is immeasurable and I am proud to share this accomplishment with you.

TABLE OF CONTENTS

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

Many daily and professional tasks, such as finding scissors in a cluttered drawer and locating an enemy within a battlefield, can require attention-demanding visual search. One technique to promote rapid detection of critical items within a search field is teaming multiple operators to search for common targets. Teaming multiple operators increases the probability that operators detect a target in a visual search task (Wiener, 1964). Although teams of operators outperform individual operators in several tasks, such as monitoring for moving voltmeter needles (Wiener, 1964), detecting a target in complex aerial pictures (Hornseth & Davis, 1967), and performing a simulated unmanned aerial vehicle (UAV) task (Garcia, et al., 2011), it remains unclear how operators' performance changes when working collaboratively compared to solitarily. For instance, if two operators collaborate in a search task, will they detect targets faster, slower, or at the same rate in comparison to their independent performance? Furthermore, do teamed operators speed target detection when their visual environments contain information about target locations? The current study employed workload capacity analysis (Townsend & Nozawa, 1995) to examine whether operators modulate response speeds when performing a visual search task collaboratively compared to solitarily, and whether providing information about the location of the target in the visual display influences collaboration in a speeded visual search task.

CHAPTER 2

LITERATURE REVIEW

Visual search is the behavior of looking for a target item among other distractor items when the location of the target is unknown. A number of professional detection operations require accurate and speedy visual search performance, such as luggage screening (McCarley, Kramer, Wickens, Vidoni, & Boot, 2004), detecting cancerous cells in chest X-rays (Kundel, Nodine, & Carmody, 1978), air traffic control (Remington, Johnston, Ruthroff, Gold, & Romera, 2000), and locating an enemy within battlefield maps (Yeh & Wickens, 2001). Unfortunately, individuals can exhibit poor visual search performance, even in searches for items defined by rudimentary features such as color, shape, and orientation (Wolfe, 1994) in a laboratory setting, raising challenges for ensuring quick and accurate visual search in real-world environments. One approach to increasing the speed and accuracy of target detection in a complex visual display is to team multiple searchers.

Team Search Performance

Pairing multiple operators improves joint performance in various visual tasks such as, detecting a target in complex aerial pictures (Hornseth & Davis, 1967), watchkeeping (Morgan & Alluisi, 1965), monitoring intensity of numerous signals (Morrissette, Hornseth, & Shellar, 1975), monitoring for moving voltmeter needles (Wiener, 1964), detecting the movement of dots of light (Waag & Halcomb, 1972), detecting defects in aircraft parts (Stanislaw, 1995), performing a sustained attention task (Ceplenski, Scerbo, & Major, 1996), and performing a simulated UAV task (Garcia et al., 2011). Operators are teamed to improve search performance in professional domains including, search and rescue, reconnaissance, and surveillance.

One early quantitative model of joint performance accuracy in a simple detection task is the independent events model (Wiener, 1964). The model, which assumes that team members' responses are independent of one another, predicts that the probability of a signal being detected by a team is:

$$P_T = 1 - (1 - P)^n, \tag{2.1}$$

where P_T is team search accuracy, P is individual search accuracy, and n is the number of members on a team. In Wiener (1964), operators detected irregular movements of a voltmeter needle in one-, two-, and three-operator teams working side-by-side. Weiner found that multi-operator teams exhibited greater probability of detection than one-operator teams, suggesting that multiple operators outperform single operators in a simple detection task.

A more advanced model of team performance in detection tasks is the group signal detection model (Sorkin, Hays, & West, 2001), which predicts signal detection judgment performance of teams of operators. Sorkin and colleagues (2001) asked operators to determine whether a display of nine analog gauges was due to signal-plus-noise or noise-alone, in one-, five-, or six-member teams. The results indicated that multi-operator teams exhibited greater performance accuracy than one-operator teams. Also, although team detection performance increased with team size, it increased at a lesser rate than predicted by an ideal model of statistically optimal team performance. Such findings indicate not only that multi-operator teams exhibit greater performance than individual operators, but also that the performance of teams may deviate from optimal performance (as specified by Sorkin and colleagues' model, 2001), as team size increases.

Teamed operators can outperform individual operators in a speeded visual detection task (Brennan, Chen, Dickinson, Neider, & Zelinsky, 2008) with stimuli that are known to produce difficult search (O among Qs; Treisman & Gormican, 1988). Brennan and colleagues (2008) asked operators to search for an O among Qs displayed at varying orientations while working independently or in pairs. Operators in paired conditions communicated using speech, shared gaze (operators' eye movements were recorded with an eye tracker and presented in real-time on their teammate's display screen), both speech and shared gaze, or neither. RT for paired conditions was determined under the OR rule, meaning that the fastest RT between paired operators constituted the team-level RT. The results indicated that in target-present trials, paired operators communicating with both speech and shared gaze demonstrated faster RT than operators performing independently.

Brennan and Enns (2015) extended the analysis of RT to a distributional level, applying Miller's race model inequality (RMI; Miller, 1982). RMI describes the statistical benefit of aggregating independent responses. Brennan and Enns (2015) asked participants to perform a visual enumeration task both individually and in pairs. The enumeration task required them to count the number of targets within a visual display and to respond as quickly as possible while maintaining high levels of accuracy. In the paired condition, teamed operators viewed stimuli on a common visual display and took turns entering responses with a shared keyboard, exchanging the keyboard each trial. Teamed operators were instructed to use any collaboration strategy that they believed would lead to best team performance. The results indicated that team search performance was better than the level predicted by the RMI from individual search performance.

Teams of operators can outperform individual operators in visual detection tasks, measured in detection accuracy (e.g., Sorkin et al., 2001; Wiener, 1964) and mean RT (e.g., Brennan et al., 2008). In speeded collaborative detection tasks (e.g., Brennan et al., 2008), however, the size of the collaborative benefit measured in mean RT depends on parametric characteristics of the underlying probability distribution, and thus, is not directly indicative of the capacity limits of a team. In other words, even when each searcher slows down his/her own search speed in a collaborative condition, mean RT can be shorter in the collaborative condition than the solitary condition due to statistical facilitation (Raab, 1962). Brennan and Enns (2015) applied RMI to collaborative cognition research, but their analysis is limited to examining whether collaborative performance is better than the level expected from individual performance, but not poorer than the expected level.

To circumvent these various constraints, the current study employed the workload capacity analysis (Townsend & Nozawa, 1995), which allows direct measurement of the capacity levels of a team, to quantify collaborative benefits in a difficult visual search task in which non-target items predicted the location of the target (e.g., Hooge & Erkelen, 1998).

Workload Capacity Analysis

In tasks such as the speeded collaborative detection task (e.g., Brennan et al., 2008), multiple team members may work simultaneously and the quickest response among the team members can determine the response of the team. Each team member in Brennan and colleagues' task, for example, concurrently searched for an O among Qs and the quickest response from a team member determined a team-level response.

The structure of Brennan and colleagues' speeded collaborative detection task is similar to that of a *redundant-targets* task (Miller, 1982; van der Heijden, La Heij, & Boer, 1983). A standard redundant-targets paradigm asks an operator to make a speeded judgment of a single target or multiple, redundant targets (e.g., Ben-David & Algom, 2009; Miller, 1982; Townsend

& Nozawa, 1995; van der Heijden et al., 1983; Wenger & Townsend, 2000). In the paradigm, each information-processing channel is assumed to process each target and the fastest processing channel of all available channels produces the first response. A typical finding in the redundant-targets paradigm is faster RT in the redundant-targets condition than in the single-target condition, an effect known as the redundancy gain.

The simplest account of the redundancy gain effect is the *unlimited-capacity, independent, parallel* (UCIP) model (Townsend & Wenger, 2004). In the UCIP model, processing speed in each channel is the same in the redundant-targets condition as the single-target condition, and each channel operates with stochastic independence – a state in which an event in one channel is probabilistically unrelated to that in another. That is, additional load of information processed in one channel does not influence the processing speed of another channel. Because the fastest processing time of the channels determines processing time of the system, statistical facilitation (Raab, 1962) often produces shorter mean RT in the redundant-targets condition compared to the single-target condition.

Capacity limitation arises when individual processing channels operate more slowly under the redundant-targets condition than the single-target condition, producing a smaller redundancy gain than expected from the UCIP model. Conversely, a super-capacity system operates when individual processing channels become faster than those operating in isolation, producing a larger redundancy gain than expected from the UCIP model (Eidels, Houpt, Altieri, Pei, & Townsend, 2011).

Whereas a redundant-targets task requires a single operator to detect single or redundant targets, a speeded collaborative detection task requires multiple operators to detect a single target. In a speeded collaborative detection task, each operator is considered an independent information-processing channel, and the fastest processing operator within a team produces the first response to the single target as a team-level response under the OR stopping rule. Like the redundant-targets task, performance improvement may appear as a redundancy gain in mean RT (Brennan et al., 2008).

Both redundant-targets and speeded collaborative detection tasks involve multiple, information-processing channels concurrently racing to produce first response to a target. Thus, analyses that assess modulations in response speeds across single- and redundant-targets conditions in redundant-targets tasks can similarly be used to assess modulations in response speeds across solitary and paired operator conditions in speeded collaborative detection tasks. By comparing response speeds in paired conditions to that predicted from solitary performance with the UCIP model, such analyses allow novel characterization of team collaboration, as any redundancy gain smaller than that predicted from the UCIP model may suggest that a team can improve beyond current performance.

One index used in the redundant-targets paradigm that can characterize information processing by a team of operators and assess team collaboration efficiency is $C(t)$ of Townsend and Nozawa's systems factorial technology (SFT; Townsend & Nozawa, 1995). SFT offers a theoretical framework and methodology for characterizing cognitive systems with a varying number of multiple and concurrent information-processing channels. It measures capacity limitations by comparing the empirical RT distribution for the redundant-targets condition to the RT distribution predicted from the UCIP model with individual RT distributions (Townsend & Nozawa, 1995).

In the SFT (Townsend & Ashby, 1978), the cumulative distribution function (CDF) in each condition is transformed to the hazard function, $h(t)$, which indicates the probability that the system will execute a response at a given *t,* given that the system has not yet done so. The hazard function serves as a measure of the instantaneous capacity of the cognitive system at a given moment. The integrated hazard function, *H(t),* defined as the integration of the hazard function over *t,* serves as a measure of the total amount of capacity that the system expended until *t.* Under the OR (self-terminating) stopping rule, $C_{OR}(t)$ is defined as the ratio of *H(t)* for the redundant-targets condition to the sum of *H(t)s* for the two single-target conditions. More formally, the capacity coefficient is defined as the following:

$$C_{OR}(t) = \frac{H_{AB}(t)}{H_A(t) + H_B(t)} \tag{2.2}$$

where subscripts A and B indicate two single-target conditions and AB indicates the redundant-targets condition. A capacity score of 1.0 denotes unlimited capacity, indicating that channels operate at the same rate under the redundant-targets and the single-target conditions. A value below 1.0 denotes capacity limitation, indicating that the processing rates of channels slow down when operating as a system in relation to operating individually. At the value of 0.5, the multi-channel system is no more efficient than serial processing. Finally, a value above 1.0 denotes super-capacity processing, indicating that the processing rates of channels speed up when operating as a system in relation to operating independently. Thus, $C_{OR}(t)$ provides a non-parametric measure of the efficiency of a multi-channel cognitive system with theory-driven benchmarks.

In a system of two operators working simultaneously in a speeded collaborative detection task, $C_{OR}(t)$ equal to 1.0 indicates that both operators maintain their own response speed when working in a team or that operators' response speeds converge as they modify their response speeds based on teammates' response speeds. A value greater than 1.0 indicates that operators' response speed increases in a collaborative condition compared to a solitary condition. On the other hand, a value less than 1.0 indicates that operators' response speed decreases when working collaboratively in comparison to solitarily.

Note that workload capacity is mathematically independent of redundancy gain, and thus redundancy gain derived from mean RT and capacity scores derived from RT distributions reveal different aspects of human performance. For example, it is possible that two pairs demonstrate identical sizes of redundancy gain but differ in levels of workload capacity. Redundancy gain is a parametric measure, and thus, a magnitude of the effect depends on underlying RT distributions. A team of operators, for instance, that exhibit slow mean responses can produce a larger redundancy gain than a team of operators whose mean responses are faster, while both teams operate using UCIP processing. Therefore, changes in capacity levels are not detectable from mean RT data.

Current Study

The current study determines whether pairs of operators performing a speeded visual detection task modulate response speed when working together compared to when working alone. Additionally, this study examines whether providing guidance to target locations in the visual display improves paired operators' search performance. Practically, many real-world search tasks involve visual imagery that contains information about the location of a target. For example, synthetic vision data regarding landmarks and friendly/hostile forces that predict locations of a target may be overlaid onto a visual display to speed UAV operators' target detection during a reconnaissance mission (e.g., Calhoun, Draper, Abernathy, Delgado, & Patzek, 2005).

Hooge and Erkelens (1998) examined the effects of non-target elements that inform the location of the target in a visual search task. Operators searched for an O among Cs displayed at varying orientations. In direction-coded conditions, the orientation of each C was drawn so that the gap in a C directed the operator toward the target. In uncoded conditions, the orientation of each C was drawn randomly. The researchers observed faster RT in direction-coded conditions than uncoded conditions, suggesting that providing target guidance information within a visual display benefits operators' search performance**.**

The present experiment asked operators to perform a speeded visual search task both in solitary and paired conditions. In the paired condition, operators performed the task on a common display in the same room, and their responses were collected as team responses employing the OR stopping rule. Each display contained a target (O) and non-target (Cs), a pair of stimuli that produces inefficient search (Treisman & Gormican, 1988). Across experimental trials, the gaps of 20% or 80% of non-targets aimed toward the target (Hooge & Erkelens, 1998).

The current work investigated how the strength of target guidance influences collaborative performance in a speeded visual search task**.** In the current study, I hypothesized that paired participants detecting targets in the same room and on a common display will benefit from greater target guidance information more than solitary participants. Paired participants can share strategies for using target guidance information and cue one another to target locations to benefit their search performance, whereas solitary participants are unable to benefit from such information sharing. Consequently, I predicted greater workload capacity in the high target guidance condition than the low target guidance condition, as the empirical RT distribution for the paired condition may exhibit a larger redundancy gain than that expected from the UCIP model:

Hypothesis 1 (H1): Participants will exhibit greater workload capacity in the high target guidance condition than the low target guidance condition.

Additionally, I hypothesized that workload capacity would increase across RT within a trial, as more information regarding the location of the target is available to operators as they take more time to complete the task. Over time, paired participants' ability to share information with one another may lead to a larger redundancy gain in the empirical RT distribution for the paired condition than that predicted by the UCIP model:

Hypothesis (H2): Workload capacity will increase across RT within a trial.

CHAPTER 3

METHOD

Experimental Design

The current study employed a 2 × 2 within-subjects design with Target Guidance (low vs. high) and Collaboration (solitary vs. paired) as independent variables and mean RT, error rates, and *Cz* as dependent variables. *Cz* is a normalized capacity score collapsed over time (Houpt & Townsend, 2012).

Participants

Thirty-four pairs of searchers (68 participants total) were recruited. Sample size was selected to provide power of .8 assuming medium effect sizes (Cohen's $d = .5$) at the alpha level of .05. Participants were sampled from the Old Dominion University undergraduate participant pool and were screened for normal or corrected-to-normal vision (Mean near acuity = 20/20; Mean far acuity = 20/20). They received two hours of research credit for their involvement in the study. Prior to data collection, the experimenter obtained approval of the study from the institutional review board at Old Dominion University.

Apparatus

Stimuli were presented on a Samsung T24C550 23.6'' LED monitor with 1920 × 1080 resolution produced by a Dell Optiplex 9020 computer. The experiment was controlled by E-Prime 2.0 (Psychology Software Tools, Pittsburgh, PA) with a refresh rate of 60 Hz. Responses were collected through keyboard presses and mouse clicks. Subjects viewed the screen at a distance of 57 cm, in a quiet room with dimmed lights.

Stimuli

Each search display contained one target item O and 35 non-target items C, drawn in light gray (6.5 cd/m^2) stroke of 0.05° on a white background. Each item featured an inner diameter of 0.90° and an outer diameter of 1.50°. Non-targets displayed a gap size of 0.31°. Stimulus items were presented in a six-column by six-row grid and each row was separated by 3.66°. Additionally, every other row was offset by 1.93° to produce a hexagonal stimulus arrangement.

Non-targets were oriented at 0, 90, 180, or 270°. In high target guidance conditions, 80% of non-targets were oriented so that the gaps faced toward the target. The remaining 20% of non-targets were drawn so that the gaps randomly faced away from the target location. In low target guidance conditions, 20% of the gaps of non-targets faced toward the target and the remaining 80% of non-targets were drawn so that the gaps randomly faced away from the target location. Targets were presented at randomly selected locations within the stimulus arrangement across experimental trials. See Figure 1 below for examples of search displays in low and high target guidance conditions.

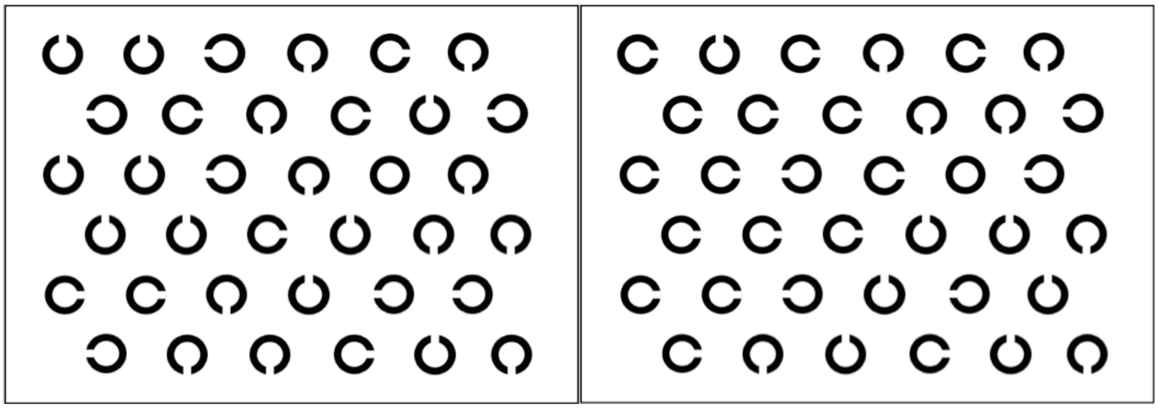

Figure 1. From left to right, search displays for low and high target guidance conditions.

Procedure

Upon participants' arrival, they were asked to review and sign an informed consent form. Participants then completed near and far visual acuity tests on Snellen eye charts to assess their ability to perform the visual search task.

In the experiment, participants were instructed to search for a target letter O among Cs. In both solitary and paired conditions, participants responded to targets by pressing the space bar on a keyboard. Participants were instructed to respond as quickly as possible. They were then asked to localize the target in a subsequent mask display to confirm their target detection.

Each trial began with a 500-ms blank screen, followed by a 400-ms fixation cross, and then the search display. The search display remained visible until a response was detected or a timeout duration of 5,000-ms elapsed. Following the detection of their responses, participants received a blank mask screen and were asked to click the location of the previously viewed target on this screen, confirming their detection of the target. The blank mask screen remained visible until the participant responded with the location of the target. Participants received feedback concerning response accuracy and correct target location at the end of each trial. A feedback message of a gray "+" for a correct response or a gray "X" for an incorrect response was presented for 750-ms. The feedback message was followed by the correct location of the target for both correct and incorrect responses.

Participants performed the identical search task in solitary and paired conditions in a counterbalanced order across pairs of participants. Each condition consisted of 20 practice trials, followed by 400 experimental trials. Each participant received blocks of trials in the low and high guidance conditions. The order of target guidance blocks was counterbalanced across participants. In the solitary condition, participants performed the task individually. In the paired condition, paired participants performed the search task on a common display while seated in the same room. Search displays in the paired condition terminated as soon as a faster participant responded.

Following the experimental task, participants received a short debriefing explaining the purpose of the experiment. The experimental session took approximately two hours to complete.

Dependent Measures

Error in target localization was defined as failure to respond to the search display prior to the 5,000-ms timeout duration, or failure to accurately indicate the location of a target on the blank mask screen.

Mean RT was calculated for solitary and paired participants across target guidance conditions only for trials with correct target localization.

$C_{OR}(t)$ was calculated separately for low and high target guidance conditions. For each target guidance condition, cumulative distribution functions (*F(t)*s) were derived from the empirical RT distributions of participants' performance in solitary and paired conditions. *F(t)*s were then transformed into integrated hazard functions (*H(t)*s; Wenger & Townsend, 2000) using the following:

$$H(t) = -\exp[F(t)] \tag{3.1}$$

$C_{OR}(t)$ was then calculated by dividing *H(t)* for the paired condition by the sum of *H(t)*s for the solitary conditions.

The statistic *Cz,* which follows a standard normal distribution and summarizes the capacity of a team throughout their performance in a condition, was also calculated from raw

$C_{OR}(t)$ scores (Houpt & Townsend, 2012). A *Cz* value of 0 denotes unlimited capacity, a positive *Cz* value denotes super-capacity, and a negative *Cz* value denotes limited capacity.

CHAPTER 4

RESULTS

Data Screening

RT data for solitary and paired conditions shorter than 250-ms were excluded from analysis, as the minimum time required to execute a speeded response in a perceptual-cognitive task is approximately 250-ms (Townsend & Wenger, 2004). Therefore, any response shorter than 250-ms was considered an anticipatory response.

Mean RT

Mean RT data for trials with correct responses were analyzed in a 2 × 2 repeated-measures ANOVA with Target Guidance (low vs. high) and Collaboration (solitary vs. paired) as independent variables. Figure 2 presents mean RT as a function of conditions. Participants' RT was longer when performing the search task alone than when paired, M = 1,549.072 ms vs. 1,196.225 ms; $F(1, 33) = 62.144$, $\eta_p^2 = .653$, $MSE = 68{,}116.981$, $p < .001$. The high guidance condition produced shorter RT than the low guidance condition, M = 1,361.275 ms vs. 1,384.021 ms; $F(1, 33) = 7.692$, $\eta_p^2 = .189$, $MSE = 2{,}287.070$, $p = .009$, and the effect of guidance on mean RT was larger for the solitary than the paired condition, $F(1, 33) = 4.367$, $\eta_p^2 = .117$, $MSE = 1{,}400.403$, $p = .044$. Post-hoc t-tests with Bonferroni corrections for multiple comparisons confirmed that the solitary condition sped their RT when provided higher target guidance, M = 1,567.151 ms vs. 1,530.992 ms; paired-samples $t(33) = 3.189$, $p = .003$, whereas paired searchers exhibited no significant difference in mean RT across guidance conditions, M = 1,200.892 ms vs. 1,191.557 ms; paired-samples $t(33) = .993$, $p = .328$.

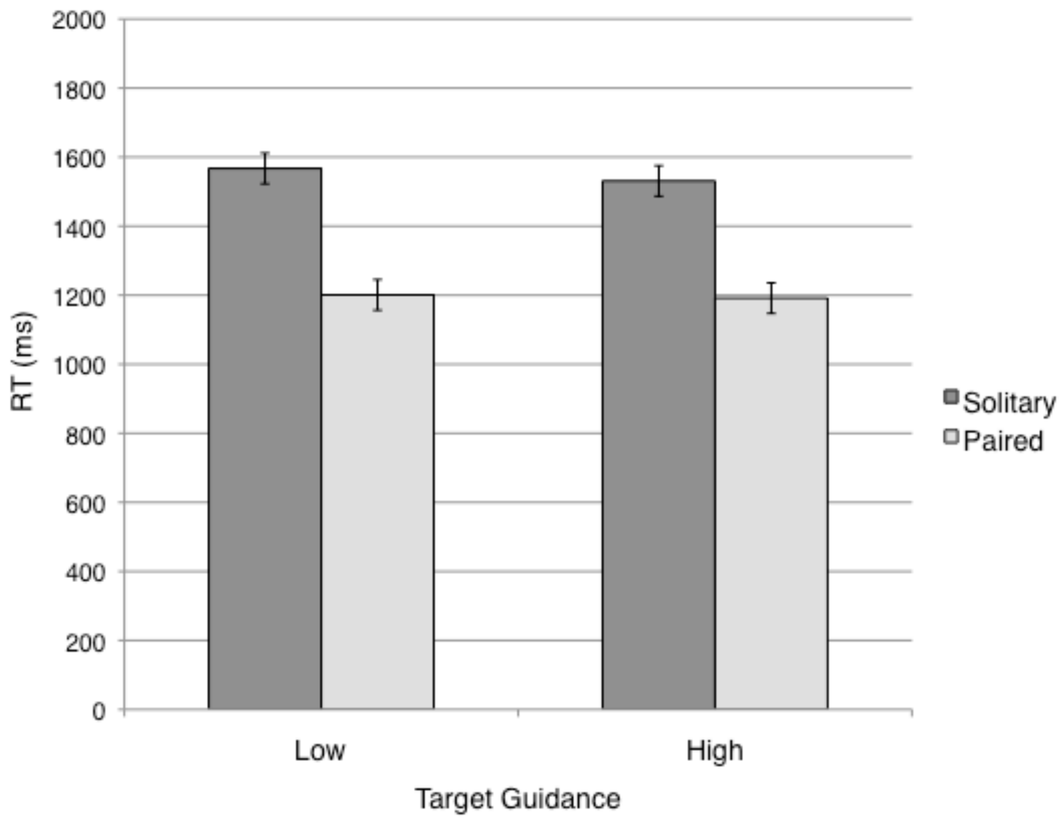

Figure 2. Mean RT data for solitary and paired searchers across target guidance conditions. Error bars represent within-subjects 95% confidence intervals (Cousineau, 2005) based on the main effect of Collaboration.

Workload Capacity

Cz values were significantly less than 0 for low target guidance, M = -1.668, 95% CI[-3.329, -.007]; one-sample $t(33) = -2.043$, $p = .049$, and high target guidance conditions, M = -1.950, 95% CI[-3.595, -.306]; one-sample $t(33) = -2.413$, $p = .022$, denoting that collaborative visual search was limited capacity in both guidance conditions. *Cz* values for the high guidance condition were numerically smaller than the low guidance condition, M = -1.950 vs. -1.668, but the effect did not reach statistical significance, paired-sample $t(33) = 1.359$, $p = .183$. See Figure 3 for *Cz* values of paired operators in low and high target guidance conditions.

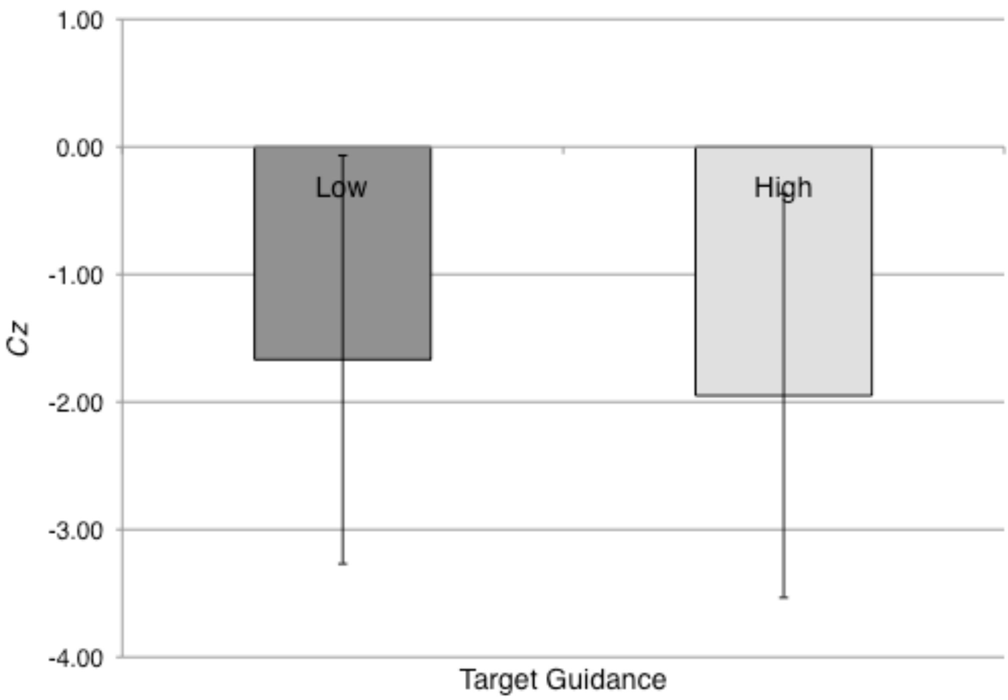

Figure 3. *Cz* values for operator pairs performing in low and high target guidance conditions. Error bars represent between-subjects 95% confidence intervals.

Figure 4 represents $C_{OR}(t)$ scores across RT. Although variability between pairs is large, visual inspection of the geometric means of capacity scores indicates that $C_{OR}(t)$ values were similar between the high and low guidance conditions. Specifically, across guidance conditions, geometric mean values began around the benchmark value of 1.0 (i.e., unlimited capacity) and then fell below 1.0 (i.e., limited capacity) at approximately 3,200-ms until the timeout duration elapsed.

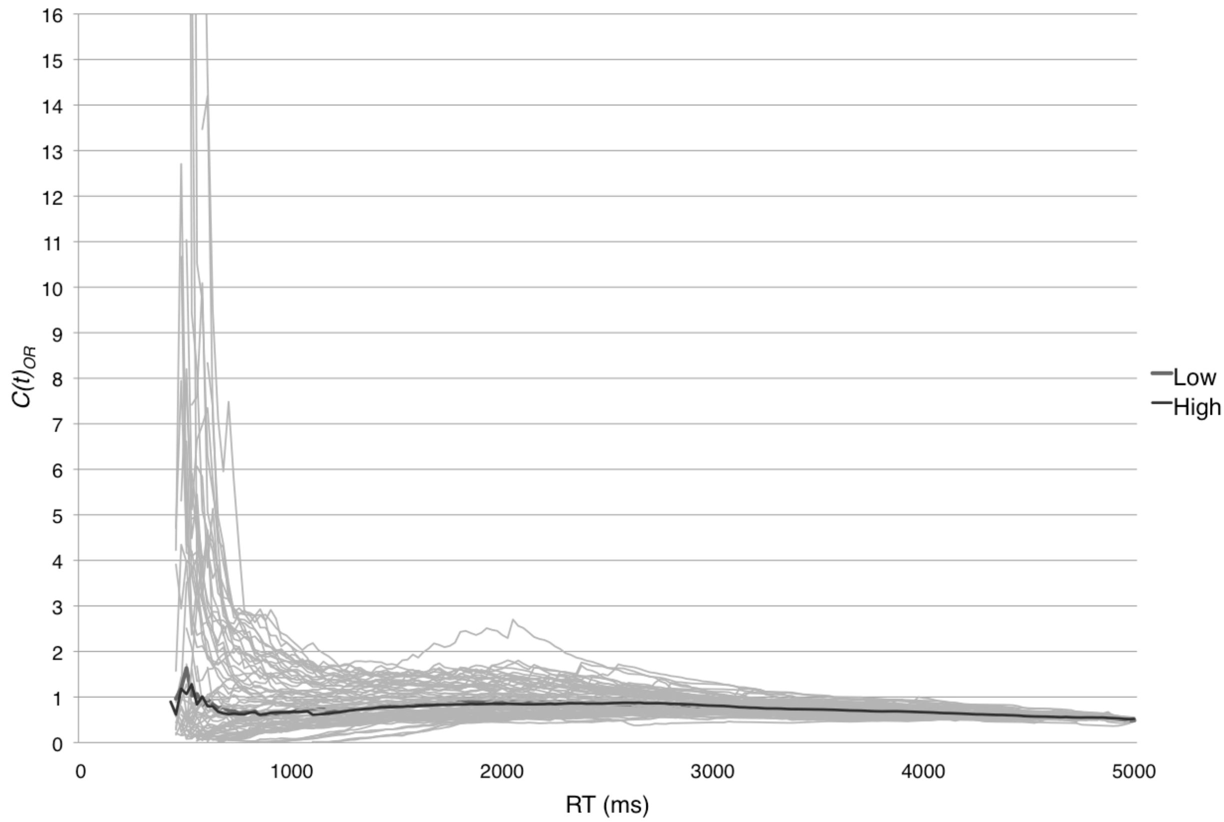

Figure 4. $C_{OR}(t)$ scores across RT for operator pairs in low and high guidance conditions. Grey and black lines represent geometric means for $C_{OR}(t)$ values for the low and high guidance conditions, respectively.

Pearson product-moment correlations were conducted to examine the relationship between *Cz* and the difference in mean RT between the solitary performances of each operator pairing across guidance conditions. These analyses were conducted to determine whether the efficiency of team collaboration depends on the difference in operators' response speeds in solitary trials. For instance, when operators' mean RT do not differ in solitary trials, they may maintain their individual response speeds in collaborative trials, as there is lesser need to modulate their response speed to match their teammate's response speed (e.g., Sherif, 1935). No significant correlations were observed for the low guidance, $r = -.032$, $n = 34$, $p = .859$, or high guidance condition, $r = -.083$, $n = 34$, $p = .641$.

Error Rates

Errors in incorrect localization and timeout were analyzed in separate 2 × 2 repeated-measures ANOVAs, identical to that used for the analysis of mean RT. Participants exhibited fewer localization errors when performing collaboratively compared to solitarily, M = .016 vs. .021; $F(1, 33) = 5.050$, $\eta_p^2 = .133$, $MSE = .000$, $p = .031$, however, the effect of target guidance, M = .018 vs. M = .020; $F(1, 33) = 1.478$, $\eta_p^2 = .043$, $MSE = 9.205\text{e-}05$, $p = .233$, and the two-way interaction were not statistically significant, $F(1, 33) = .761$, $\eta_p^2 = .023$, $MSE = 9.281\text{e-}05$, $p = .389$. For timeout errors (See Figure 5), the two-way interaction was statistically significant, $F(1, 33) = 4.977$, $\eta_p^2 = .131$, $MSE = 4.628\text{e-}05$, $p = .389$, indicating that paired searchers exhibited less timeout errors than solitary searchers, M = .002 vs. M = .018, across target guidance conditions, paired-sample $t(67) = 7.884$, $p < .001$. Thus, the data gave no evidence for speed-accuracy tradeoffs.

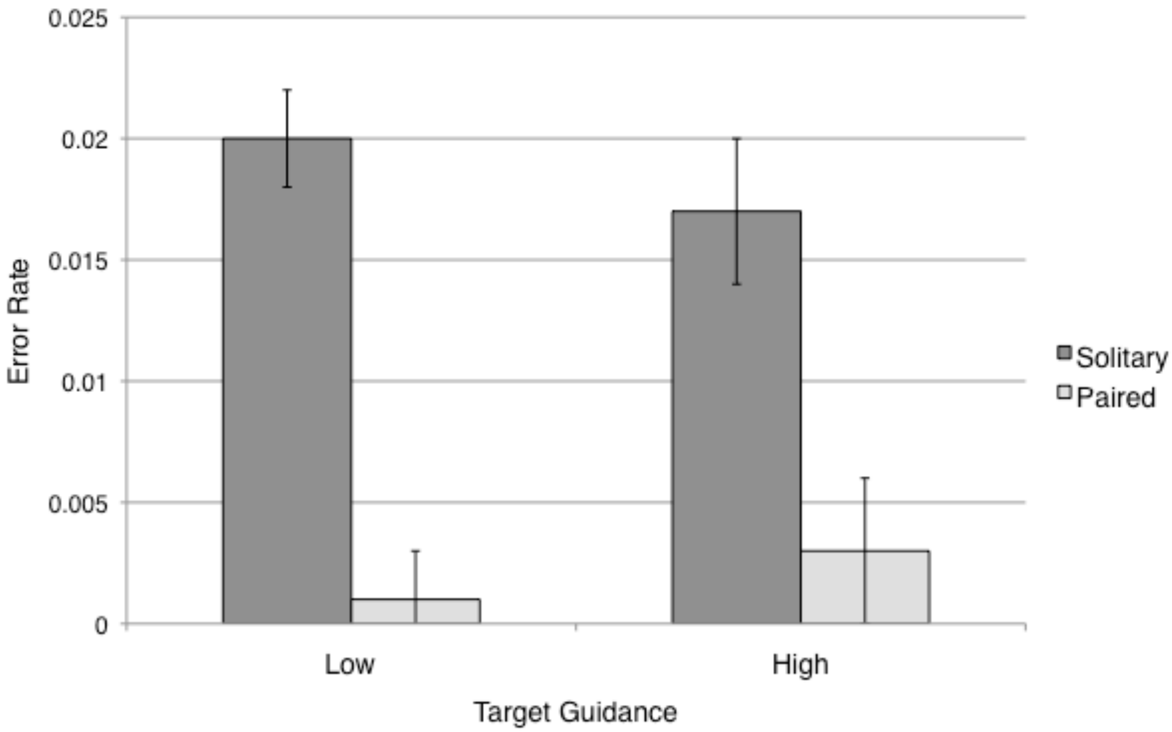

Figure 5. Timeout errors for solitary and paired searchers across target guidance conditions. Error bars represent within-subjects 95% confidence intervals (Cousineau, 2005) based on the main effect of Collaboration.

Order Effects

Mean RT. Effects of the order that participants completed solitary and paired conditions were analyzed in a 2 (low guidance vs. high guidance) × 2 (solitary vs. paired) × 2 (solitary condition completed first vs. paired condition completed first) split-plot ANOVA on mean RT. The Order × Collaboration interaction was significant, $F(1, 32) = 9.006$, $\eta_p^2 = .220$, $MSE = 54{,}818.210$, $p = .005$, suggesting that the effect of collaboration was larger when participants performed the solitary condition first compared to the paired condition (See Figure 6). Post-hoc t-tests with Bonferroni corrections for multiple comparisons confirmed that solitary participants exhibited significantly shorter RT when they performed the paired condition first compared to the solitary condition, M = 1,442.653 ms vs. 1,655.491 ms; independent-sample $t(66) = 3.847$, $p < .001$, whereas paired participants' mean RT did not differ depending on the order in which they completed collaboration conditions, M = 1,182.145 ms vs. 1,210.304 ms; independent-sample $t(66) = -0.347$, $p = .730$.

The main effects of Collaboration, $F(1, 32) = 77.220$, $\eta_p^2 = .707$, $MSE = 54{,}818.200$, $p < .001$, and Target Guidance, $F(1, 32) = 8.100$, $\eta_p^2 = .202$, $MSE = 2{,}171.844$, $p = .008$, and the Collaboration × Target Guidance interaction, $F(1, 32) = 4.245$, $\eta_p^2 = .117$, $MSE = 1{,}440.745$, $p = .048$, remained statistically significant. The main effect of Order, $F(1, 32) = 1.037$, $\eta_p^2 = .031$, $MSE = 279{,}437.539$, $p = .316$, the Order × Target Guidance interaction, $F(1, 32) = 2.751$, $\eta_p^2 = .079$, $MSE = 2{,}171.844$, $p = .107$, and the three-way interaction effect , $F(1, 32) = 0.076$, $\eta_p^2 = .002$, $MSE = 1{,}440.745$, $p = .785$, were not statistically significant.

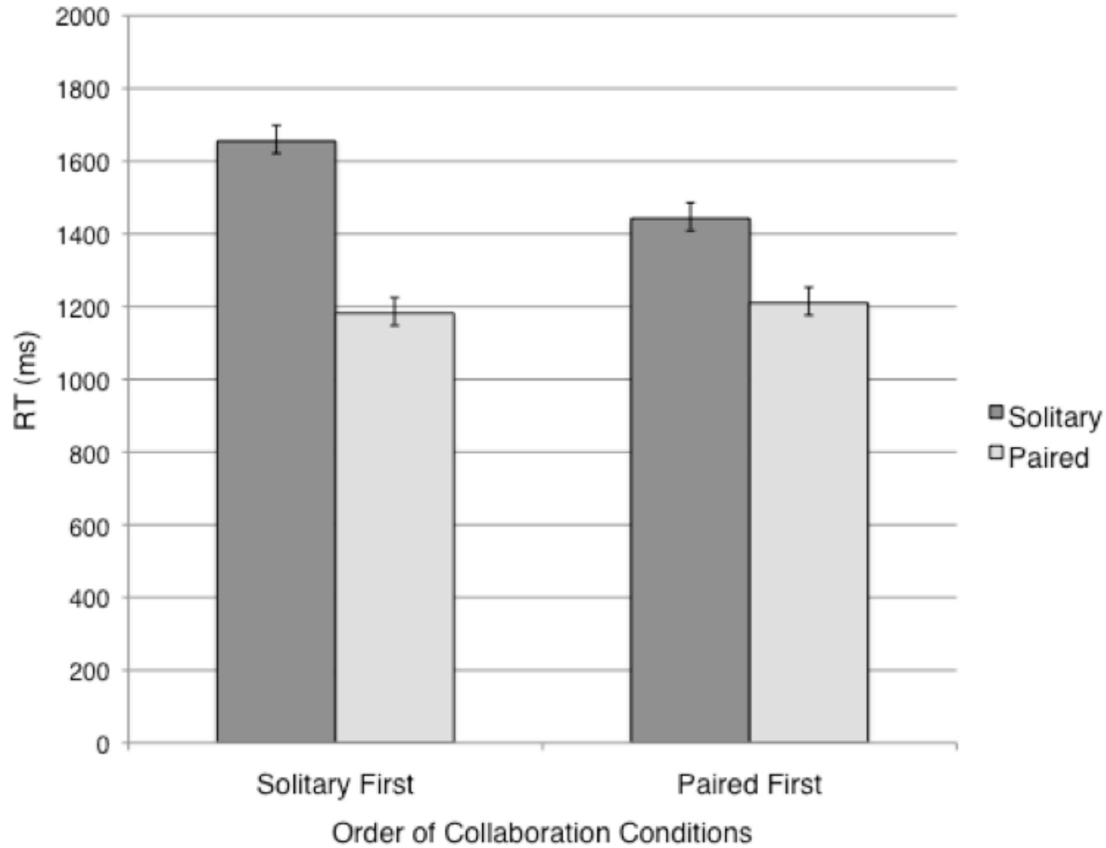

Figure 6. Collaboration × Order interaction across target guidance conditions for mean RT. Error bars represent within-subjects 95% confidence intervals (Cousineau, 2005) based on the main effect of Collaboration.

Workload capacity. Order effects on *Cz* were also analyzed in a 2 (low guidance vs. high guidance) × 2 (solitary condition completed first vs. paired condition completed first) split-plot ANOVA to determine whether the efficiency of team collaboration was influenced by the order in which participants performed solitary and paired conditions. *Cz* was greater when participants performed the solitary condition first compared to the paired condition first, M = 0.671 vs. -4.289; $F(1, 32) = 12.889$, $\eta_p^2 = .287$, $MSE = 32.454$, $p = .001$. However, the two-way interaction, $F(1, 32) = 0.360$, $\eta_p^2 = .011$, $MSE = 0.747$, $p = .553$, was not statistically significant. The effect of target guidance remained non-significant, $F(1, 32) = 1.811$, $\eta_p^2 = .054$, $MSE = 0.747$, $p = .188$. Cz values were not significantly less than zero across target guidance conditions when participants performed the solitary condition first, M = 0.671, 95% CI[-0.930, 2.272]; one-sample $t(33) = 0.853$, $p = .400$, denoting unlimited capacity. Cz values were significantly less than zero across target guidance conditions when participants performed the paired condition first, M = -4.289, 95% CI[-5.457, -3.122]; one-sample $t(33) = -7.476$, $p < .001$, denoting limited capacity.

CHAPTER 5

DISCUSSION

The current study examined whether display information predicting the location of a target speeds operators' responses in a visual search task similarly when searching collaboratively to solitarily. Like in previous studies, operators responded faster when searching collaboratively compared to solitarily (Brennan et al., 2008; Brennan & Enns, 2015) and when non-targets predicted the target location at a greater probability (Hooge & Erkelens, 1998). The magnitude of the effect of target guidance in the current study was markedly smaller than that reported in Hooge and Erkelens (1998). Hooge and Erkelens (1998) reported an average RT benefit of approximately 2,375-ms, whereas the current participants produced that of 23-ms. Such discrepancy in effect sizes may be due to the different manipulation used in the current study than the original Hooge and Erkelens (1998). In Hooge and Erkelens (1998), non-targets either did not predict or perfectly predicted the target location (0% vs. 100% guidance). Non-targets in the current study predicted the target location at a probability of either 20% or 80%. Thus, the benefit of target guidance may depend on the strength of target guidance. Interestingly, the benefit of the guidance information was more pronounced when searching solitarily than collaboratively, suggesting that providing target guidance may reduce response speeds more when searchers work alone compared to collaboratively.

Workload capacity analysis revealed that collaborative search performance was capacity limited: Operators responded more slowly when searching collaboratively compared to solitarily. Thus, operators reduced their response speeds when working collaboratively compared to solitarily in anticipation of their teammate's response, especially when the first response was made at later than 3,200-ms. This result indicates that operators may maintain their search speed for the first 3,200-ms of a collaborative search trial, and responses of either a single searcher, or both slow down later in a trial. This trend was similar regardless of target guidance condition. The observed trend suggests that target guidance does not prevent slowing of responses when working collaboratively. Moreover, *Cz* was not correlated with the difference in mean RT between the solitary performances of each operator pairing. This finding suggests that team collaboration efficiency is unrelated to the difference in paired operators' performance when working solitarily.

Why are operators unable to maintain their search speed throughout the trial duration when working collaboratively? One potential explanation for this behavior is *social loafing* (Karau & Williams, 1993), which is a tendency for individual operators to expend less effort to achieve a goal when working in teams compared to when working independently. Social loafing has been demonstrated in several tasks including detection of infrequently occurring signals (Harkins & Szymanski, 1989), rope pulling (Ingham, Levinger, Graves, & Peckman, 1974), and brainstorming (Harkins & Jackson, 1985). Participants in the current study may have reduced their effort toward the task in the presence of a teammate, and thus, exhibited slower response speeds in collaborative trials than solitary (i.e., limited capacity).

Reductions in operators' response speeds in collaborative trials may also be due to operators spending time coordinating responses (e.g., speaking about how to use target guidance information, cueing one another to target locations) with their teammate. For example, Brennan et al. observed faster RT when paired operators communicated using shared gaze alone than with both shared gaze and speech. Coordination using speech requires time and may slow paired operators' responses to targets. As operators in the current study were allowed to adopt any coordination strategy, it is possible that their efforts to coordinate with their teammate slowed their individual response speeds.

An order effect was observed in that solitary participants exhibited faster RT when they performed collaboratively first compared to solitarily first. Sherif (1935) observed a similar order effect when participants performed a visual illusion task in which they estimated the distance of movements of light in a dark room both solitarily and collaboratively. The order that participants completed solitary and collaborative conditions was manipulated. In collaborative conditions, team members were seated next to one another and each team member said aloud their estimate of the distance the light moved in a random order. When participants completed the solitary condition first, their estimations of distance varied between one another in solitary trials, and then converged later in collaborative trials. Alternatively, when participants completed the collaborative condition first, there was little variability between participants' estimations in collaborative trials, and participants continued to estimate similarly to one another in subsequent solitary trials. Such findings provide explanation for why solitary participants in the current study performed faster after completing the collaborative condition than when completing the solitary condition first, as information regarding teammate's responses in collaborative trials may influence participants' response speeds in subsequent solitary trials.

Additionally, paired participants collaborated more efficiently (greater *Cz*) when they performed the solitary condition first compared to the collaborative condition. Specifically, across target guidance conditions, participants maintained individual response speeds in collaborative trials (i.e., unlimited capacity) when they performed the solitary condition first, and slowed individual response speeds in collaborative trials (i.e., limited capacity) when they performed the paired condition first. This result is unexpected, as one would predict that operators would be less likely to modulate individual performance in the solitary condition, after perceiving a teammate's performance in the paired condition (Sherif, 1935), compared to when completing the solitary condition first. Note that capacity scores are based on the ratio of the integrated hazard function for the paired condition to the sum of integrated hazard functions for the solitary conditions. If paired performance is comparable across order of collaboration conditions (as observed from mean RT analysis), then capacity scores are inversely related to participants' performance in the solitary conditions. The solitary first condition produced longer mean RT for solitary performance than the paired first condition. Such a pattern may suggest that solitary participants expended less capacity over *t* (measured by integrated hazard function) when they completed the solitary condition first compared to the paired condition first, leading to a smaller denominator for the capacity coefficient formula (Eq. 2.2) and greater capacity in the solitary first condition than the paired first condition. As noted in Limitations below, however, the current analysis is unable to identify which member of each pair modulated response speed, and further research is necessary for examining this order effect on collaborative performance.

Practical Implications

The results of the current study suggest that providing target guidance information in a visual search task may benefit solitary searchers more than collaborating searchers. For example, in a search for an enemy target on a common battlefield map, operators may quicken responses when provided synthetic vision data within their visual display that predict the location of a target (e.g., prior positions of the target, positions of target's known allies, or positions of the target's assets) more when performing solitarily compared to collaboratively.

The current study also highlights the utility of the workload capacity analysis as a novel technique for assessing team collaboration in a visual search task. Whereas mean RT analysis indicated that paired searchers outperformed solitary searchers (i.e., redundancy gain), workload capacity analysis further revealed that individual operators within the pairs were actually slowing their response speeds when working collaboratively compared to solitarily. That is, paired operators exhibited a smaller redundancy gain than that expected from the UCIP model, based on their individual response speeds from the solitary condition. Thus, the benefit of collaboration measured in mean RT can further increase if searchers maintain their own response speed when working collaboratively.

Similar workload capacity analyses may be conducted to examine collaboration of human operators in other speeded response tasks, such as detecting enemy targets in battlefield displays (Yeh & Wickens, 2001), detecting conflicts in air traffic control displays (Remington, Johnston, Ruthroff, Gold, & Romera, 2000), and visual search in human-automation teams (Morley, Yamani, & McCarley, in preparation; Yamani & McCarley, 2016). For contexts in which team responses are determined using an AND stopping rule, an alternative measure, $C_{AND}(t)$, may be used to assess whether individual operators modulate their processing speeds following a response from their teammate (e.g., Neider, Chen, Dickinson, Brennan, & Zelinsky, 2010).

Limitations and Future Research

Limitations of the current study include an inability to determine which participants reduced individual response speeds in the paired condition. Workload capacity analysis is able to indicate whether paired operators exhibit as large a redundancy gain as that predicted from the UCIP model, based on their solitary performance. However, because the fastest responding participant in each paired trial determined team-level RT under the OR stopping rule, the response behavior of the non-responding participant was not accounted for. Thus, the workload capacity analysis used in the current study is unable to determine which operator changed response speeds in the collaborative condition.

An additional limitation is an inability to determine the mechanisms causing operators to slow down in collaborative conditions. *Cz* characterizes team collaboration efficiency, but is unable to indicate why operators perform differently in paired and solitary conditions. Further research is needed to determine mechanisms (e.g., social loafing) that lead operators to reduce processing speeds when working in teams.

Last, operators were paired based on common scheduling, and consequently, the effect of operator pairing characteristics on collaborative performance was not examined. Future research may investigate whether paired searchers exhibit more efficient collaboration when they are familiar with their teammate than if the two are strangers (Evans & Dion, 1991; Nonose, Yoda, Kanno, & Furuta, 2015), if they are paired based on similar performance abilities, or when they receive training to cooperate prior to experiments. Additional topics for investigation might include the influence of operating from remote locations linked by shared gaze technology (Brennan et al., 2008) and team size (Sorkin, Hays, & West, 2001) on team collaboration.

CHAPTER 6

CONCLUSION

Numerous professional tasks require teamed operators to simultaneously search for targets on a common visual display. The workload capacity analysis offers a novel technique for directly gauging capacity of paired operators in speeded cognitive tasks, indicating whether operators speed up, slow down, or maintain processing speeds when working together compared to solitarily. The current study employed a workload capacity analysis to determine whether operators modulated their individual performance in a speeded visual search task when working collaboratively, and whether their collaboration was influenced by the amount of target guidance provided to them in their visual displays. Teamed operators slowed their response speeds when performing the task in pairs compared to solitary performance, regardless of the target guidance manipulation. Similar workload capacity analyses may be employed to measure collaboration in other speeded response tasks, allowing researchers to determine when operators' response speeds can be improved beyond current performance.

REFERENCES

Ben-David, B. M., & Algom, D. (2009). Species of redundancy in visual target detection. *Journal of Experimental Psychology: Human Perception and Performance*, *35*(4), 958-976.

Brennan, S. E., Chen, X., Dickinson, C. A., Neider, M. B., & Zelinsky, G. J. (2008). Coordinating cognition: The costs and benefits of shared gaze during collaborative search. *Cognition*, *106*(3), 1465-1477.

Brennan, A., & Enns, J. (2015). When two heads are better than one: Interactive versus independent benefits of collaborative cognition. *Psychonomic Bulletin & Review,* 1076-1082.

Calhoun, G. L., Draper, M. H., Abernathy, M. F., Patzek, M., & Delgado, F. (2005). Synthetic vision system for improving unmanned aerial vehicle operator situation awareness. In *Defense and Security* (Vol. 5802, pp. 219-230).

Ceplenski, P. J., Scerbo, M. W., & Major, D. A. (1996). Multiple monitors and knowledge of results in vigilance: The decrement still wins. In *Proceedings of the Human Factors and Ergonomic Society Annual Meeting* (Vol. 40, No. 23, pp. 1222-1226).

Cousineau, D. (2005). Confidence intervals in within-subject designs: A simpler solution to Loftus and Masson's method. *Tutorials in Quantitative Methods for Psychology*, *1*(1), 42-45.

Eidels, A., Houpt, J. W., Altieri, N., Pei, L., & Townsend, J. T. (2011). Nice guys finish fast and bad guys finish last: Facilitatory vs. inhibitory interaction in parallel systems. *Journal of Mathematical Psychology*, *55*(2), 176-190.

E-Prime 2.0 [Apparatus and Software]. (2014). Pittsburgh, PA: Psychology Software Tools.

Evans, C. R., & Dion, K. L. (1991). Group cohesion and performance a meta-analysis. *Small Group Research*, *22*(2), 175-186.

Garcia, A., Baldwin, C., Funke, M., Funke, G., Knott, B., Finomore, V., & Warm, J. (2011). Team vigilance the effects of co-action on workload in vigilance. In *Proceedings of the Human Factors and Ergonomic Society Annual Meeting* (Vol. 55, No. 1, pp. 1185-1189).

Harkins, S. G., & Jackson, J. M. (1985). The role of evaluation in eliminating social loafing. *Personality and Social Psychology Bulletin*, *11*(4), 457-465.

Harkins, S. G., & Szymanski, K. (1989). Social loafing and group evaluation. *Journal of Personality and Social Psychology*, *56*(6), 934.

Hooge, I. T. C., & Erkelens, D. W. (1998). Adjustment of fixation duration in visual search. *Vision Research*, *38*(9), 1295-1302.

Hornseth, J., & Davis, J. (1967). Individual and two-man team target finding performance. *Human Factors, 9*(39), 39-43.

Houpt, J. W., & Townsend, J. T. (2012). Statistical measures for workload capacity analysis. *Journal of Mathematical Psychology*, *56*, 341-355.

Ingham, A. G., Levinger, G., Graves, J., & Peckham, V. (1974). The ringelmann effect: Studies of group size and group performance. *Journal of Experimental Social Psychology*, *10*(4), 371-384.

Karau, S. J., & Williams, K. D. (1993). Social loafing: A meta-analytic review and theoretical integration. *Journal of Personality and Social Psychology*, *65*(4), 681-706.

Kundel, H., Nodine, C., & Carmody, D. (1978). Visual scanning, pattern recognition and decision-making in pulmonary nodule detection. *Investigative Radiology, 25*, 890-898.

McCarley, J. S., Kramer, A. F., Wickens, C. D., Vidoni, E. D., & Boot, W. R. (2004). Visual skills in airport-security screening. *Psychological Science*, *15*(5), 302-306.

Miller, J. (1982). Divided attention: Evidence for coactivation with redundant signals. *Cognitive Psychology*, *14*(2), 247-279.

Morgan, B. B., & Alluisi, E. A. (1965). On the inferred independence of paired watchkeepers. *Psychonomic Science*, *2*(1-12), 161-162.

Morley, Yamani, & McCarley, (in preparation). Workload capacity analysis of human automation interaction in a visual search task.

Morrissette, J. O., Hornseth, J. P., & Shellar, K. (1975). Team organization and monitoring performance. *Human Factors*, *17*(3), 296 – 300.

Neider, M. B., Chen, X., Dickinson, C.A., Brennan, S. E., & Zelinsky, G. J. (2010). Coordinating spatial referencing using shared gaze. *Psychonomic Bulletin & Review, 17,* 718-724.

Nonose, K., Yoda, Y., Kanno, T., & Furuta, K. (2015). An exploratory study: A measure of workload associated with teamwork. *Cognition, Technology & Work*, 1-10.

Raab, D. H. (1962). Division of psychology: Statistical facilitation of simple reaction times. *Transactions of the New York Academy of Sciences, 24*, 574-590.

Remington, R., Johnston, J., Ruthroff, E., Gold, M., & Romera, M. (2000). Visual search in complex displays: Factors affecting conflict detection by air traffic controllers. *Human Factors, 42*(3), 349-366.

Sherif, M. (1935). A study of some social factors in perception. *Archives of Psychology (Columbia University)*.

Sorkin, R. D., Hays, C. J., & West, R. (2001). Signal-detection analysis of group decision making. *Psychological Review*, *108*(1), 183-203.

Stanislaw, H. (1995). Effect of type of task and number of inspectors on performance of an industrial inspection-type task. *Human Factors*, *37*(1), 182-192.

Townsend, J. T., & Ashby, F. G. (1978). Methods of modeling capacity in simple processing systems. *Cognitive Theory*, *3*, 200-239.

Townsend, J., & Nozawa, G. (1995). Spatio-temporal properties of elementary perception: An investigation of parallel, serial, and coactive theories. *Journal of Mathematical Psychology, 39*, 321-359.

Townsend, J. T., & Wenger, M. J. (2004). A theory of interactive parallel processing: New capacity measures and predictions for a response time inequality series. *Psychological Review*, *111*(4), 1003.

Treisman, A., & Gormican, S. (1988). Feature analysis in early vision: Evidence from search asymmetries. *Psychological Review*, *95*(1), 15-48.

Van der Heijden, A. H., La Heij, W., & Boer, J. P. A. (1983). Parallel processing of redundant targets in simple visual search tasks. *Psychological Research*, *45*(3), 235-254.

Waag, W. L., & Halcomb, C. G. (1972). Team size and decision rule in the performance of simulated monitoring teams. *Human Factors*, *14*(4), 309-314.

Wenger, M., & Townsend, M. J. (2000). Basic response time tools for studying general processing capacity in attention, perception, and cognition. *The Journal of General Psychology, 127*(1), 67-99.

Wiener, E. L. (1964). The performance of multi-man monitoring teams. *Human Factors*, *6*(2), 179-184.

Wolfe, J. M. (1994). Guided search 2.0: A revised model of visual search. *Psychonomic Bulletin & Review*, *1*(2), 202-238.

Yamani, Y., & McCarley, J. S. (2016). Workload capacity: A response time–based measure of automation dependence. *Human Factors*, *58*(3), 462-471.

Yeh, M., & Wickens, C. D. (2001). Display signaling in augmented reality: Effects of cue reliability and image realism on attention allocation and trust calibration. *Human Factors, 43*(3), 355-365.

VITA

Christopher Morley

Old Dominion University
Department of Psychology
Norfolk, VA 23529

Education and Training

Ph.D. **Old Dominion University,** *Norfolk, VA*
Human Factors Psychology, 2018 (Expected)
Advisor: Yusuke Yamani, Ph.D.

M.S. **Old Dominion University,** *Norfolk, VA*
Experimental Psychology, 2016
Advisor: Yusuke Yamani, Ph.D.

B.S. **State University of New York, College at Oneonta,** *Oneonta, NY*
Psychology, 2013
Advisor: Lawrence Guzy, Ph.D.

Background

Christopher Morley is a third year Human Factors Psychology Ph.D. student at Old Dominion University. He works in the Applied Cognitive Performance Lab under the advisement of Dr. Yusuke Yamani. His research interests include human-automation interaction, collaborative cognition, and human-computer interaction.