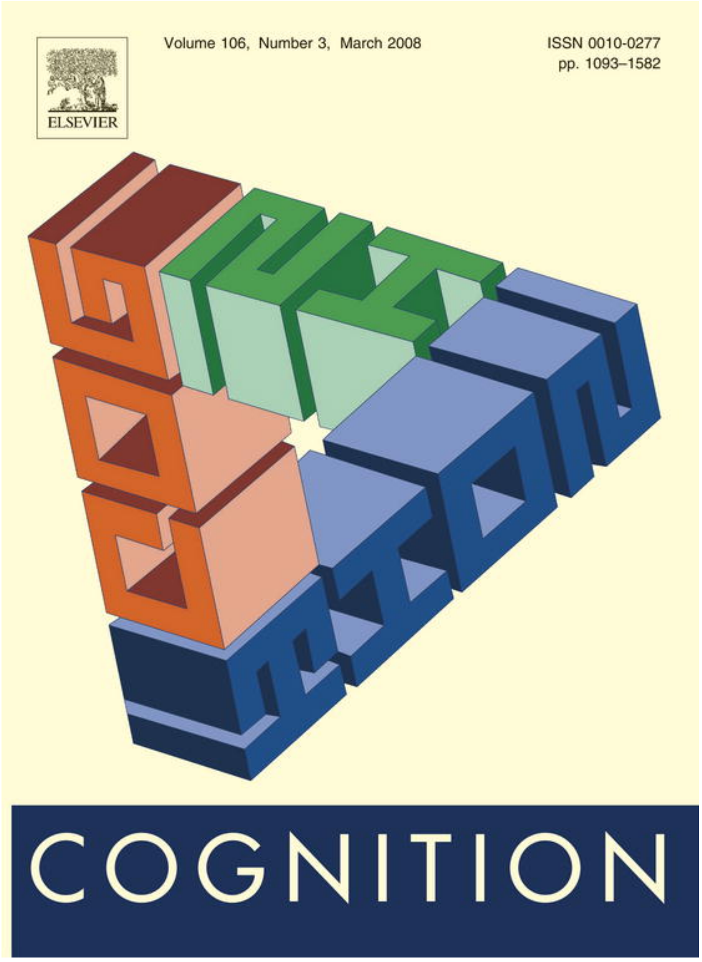
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Brief article

Coordinating cognition: The costs and benefits of shared gaze during collaborative search

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Abstract

Collaboration has its benefits, but coordination has its costs. We explored the potential for remotely located pairs of people to collaborate during visual search, using shared gaze and speech. Pairs of searchers wearing eyetrackers jointly performed an O-in-Qs search task alone, or in one of three collaboration conditions: shared gaze (with one searcher seeing a gaze-cursor indicating where the other was looking, and vice versa), shared-voice (by speaking to each other), and shared-gaze-plus-voice (by using both gaze-cursors and speech). Although collaborating pairs performed better than solitary searchers, search in the shared gaze condition was best of all: twice as fast and efficient as solitary search. People can successfully communicate and coordinate their searching labor using shared gaze alone. Strikingly, shared gaze search was even faster than shared-gaze-plus-voice search; speaking incurred substantial coordination costs. We conclude that shared gaze affords a highly efficient method of coordinating parallel activity in a time-critical spatial task.

Keywords: Coordination; Eye gaze; Collaborative visual search; Shared gaze; Communication; Grounding; Shared attention

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1. Introduction

Cognitive processing is traditionally studied in people working alone, isolated from opportunities to interact or collaborate with others. But much of cognition – be it language or memory – is situated in social contexts (for reviews in the language domain, see Pickering & Garrod, 2004; Schober & Brennan, 2003; in the memory domain, see Hoppe, 1962; Steiner, 1972; Stephenson, Clark, & Wade, 1986; Weldon, 2000; Weldon & Bellinger, 1997). One clear finding from the memory literature is that group products are not simple combinations of individual products. When products of "true" groups (people interacting to recall items together) are compared to those of "nominal" groups (formed by pooling products of the same number of individuals recalling alone, excluding duplicate items), nominal groups recall more than true groups (e.g., Lorge & Solomon, 1962; Ryack, 1965; Weldon & Bellinger, 1997).

Most of this previous work has focused on the products of collaboration; the processes used to coordinate interactions during a collaborative task are still not well understood (Ohaeri, 1998). Coordination in communication has been studied using the grounding framework (Brennan, 2005; Clark, 1996; Clark & Brennan, 1991; Gergle, Kraut, & Fussell, 2004), which proposes that partners in a collaborative task monitor and coordinate their behavior to minimize their collective effort, as well as the costs that arise in joint activity. In this study, we use the grounding framework and a visual search task to study the behavioral coordination underlying collaboration.

Visual search is ideal for studying the moment-by-moment interactions required by efficient coordination, as it is a time-critical task with relatively well understood spatio-temporal dynamics (Zelinsky, 2005; Zelinsky, Rao, Hayhoe, & Ballard, 1997). Although much is known about solitary visual search (for review, see Wolfe, 1998), collaborative search remains unexplored. Yet many real-world tasks involve people searching together, be it two children jointly looking through a picture book or a security team trying to find a suspect in a crowd. We explored the bi-directional communication of gaze cursors between remotely located partners and compare the independent contributions of shared gaze and speech in coordinating collaborative search behavior. An O-in-Qs search task was used to address three basic questions:

(1) *To what extent does collaborative search produce meaningful benefits over solitary search?* Searching collaboratively for a target will necessarily incur some coordination costs. Given that solitary search is already extremely efficient (e.g., Dickinson & Zelinsky, 2005), large coordination costs may cause partners to abandon collaboration and to search independently. At the other extreme, partners might perfectly divide the task labor, meaning that collaborative search, at its most efficient, might require half the time of solitary search.
(2) *How do people coordinate during collaborative search?* Coordination relies on devices such as precedent, convention, and monitoring a partner's behavior (Clark, 1996; Lewis, 1979). But efficient collaborative search requires not only

partner monitoring; partners must also agree on who should search where, establish a virtual boundary demarcating these regions, and set rules for stopping a target-absent search (e.g., immediately upon reaching the boundary, or after partial inspection of the partner's region). This introduces a potential overhead for collaborative search that is not part of solitary search. To observe the coordination strategies used to make these decisions, we monitored searchers' eye movements, which are uniquely informative about incremental processes leading up to behavioral decisions (Griffin & Bock, 1998; Meyer, Sleiderink, & Levelt, 1998; Tanenhaus, Spivey-Knowlton, Eberhard, & Sedivy, 1995).

(3) *What communication medium best mediates time-critical collaborative search?* We explored the independent benefits to collaboration for speech and shared gaze. Eye movements were therefore used as both a dependent measure and communication medium in our study. The *speech advantage hypothesis* predicts that any costs incurred by speaking (e.g., negotiating strategies for dividing the display or stopping target-absent searches) are outweighed by benefits (e.g., efficient division of labor), resulting in a net improvement in performance. This hypothesis follows from early findings that adding a speech channel doubles collaboration efficiency in a variety of media (Chapanis, Ochsman, Parrish, & Weeks, 1972). However, visual search may be difficult to coordinate using speech, as spatial information can be hard to communicate verbally. Speech is also inherently sequential and takes time to unfold, potentially producing a *speech disadvantage* in time-critical collaborative search.

The *gaze advantage hypothesis* predicts a benefit in performance when partners can share gaze. Seeing where a partner is looking communicates task-relevant spatial information easily (e.g., Argyle & Cook, 1976; Goodwin, 1981; Kendon, 1967). To the extent that people are able to accurately monitor and use this gaze information (Hanna & Brennan, 2007; Monk & Gale, 2002; Velichkovsky, 1995), a gaze advantage might be expected as partners divide the search labor. However, if monitoring gaze is difficult or distracting, costs might outweigh benefits, resulting in a *gaze disadvantage*.

2. Method

2.1. Apparatus

Two searchers (A and B) in different rooms, each wearing a head-mounted Eyelink II eyetracker (SR Research), searched for targets using shared gaze and/or speech (Fig. 1). Shared gaze was implemented by sending the eye position from each searcher's eyetracker to the other's screen, displayed as a gaze cursor. A bi-directional microphone-speaker system was used to implement a speech channel. The first searcher to register a response terminated the trial for both.

Fig. 1. Schematic of our shared gaze collaborative search system. Searchers were seated in front of identical 19 in. SVGA computer monitors in separate rooms. Synchronized Pentium-based computers outputted displays to each monitor, so that each searcher saw the same stimulus and performed the same search task. Display and eyetracker computers were connected via an Ethernet hub, enabling the bi-directional exchange of gaze signals: the eye position from each searcher's eyetracker could be displayed as a gaze cursor (a 1.7° yellow ring) superimposed over the other's search display. An estimated 24 ms was needed to obtain a fixation position from A and to draw the corresponding gaze cursor on B's monitor, based on a 500 Hz gaze position sampling frequency and a 100 Hz monitor refresh rate.

2.2. Stimuli and design

Participants searched for an O among Qs oriented at 0°, 90°, 180°, and 270°. Displays subtended $28° \times 21°$. The target subtended 0.61° and the "tail" of the distractors subtended 0.07°. The 192 trials were evenly divided between two randomly interleaved set size (21 or 35 items) and target-present and target-absent conditions.

There were 5 between-searcher conditions. Four involved pairs, who communicated using speech, gaze, both, or neither, with the first searcher to register a response terminating the trial for both. In the shared-gaze-only condition (SG), each searcher knew in near real-time where the other was looking. In the shared-voice-only condition (SV), searchers communicated via the speech channel, and in the shared-gaze-plus-voice condition (SG+V) searchers communicated with both speech and gaze cursors. In the no-communication condition (NC), searchers participated simultaneously, but could not communicate. The fifth condition was a standard one-person search task (1P).

2.3. Participants and procedure

Forty naive graduate students from Stony Brook University participated, 8 in the 1P condition and 32 as pairs in the SG, SV, SG+V, and NC conditions (4 pairs/condition).

A trial began when paired or solitary searchers pressed a button while fixated on a central cross. Searchers were instructed to indicate the presence or absence of targets as quickly and accurately as possible by pressing one of two buttons. Paired searchers were encouraged to cooperate both by instruction and payoff matrix[1], but no

[1] Both partners received a 3-cent reward for a correct response or a 6-cent penalty for an error. Solitary searchers received the same payoff matrix.

specific collaborative strategies were suggested. Any strategies were devised and implemented on the fly, within the constraints imposed by the communication condition. As soon as one searcher responded, both received feedback about accuracy and target location (the target was highlighted in target-present trials). There were 16 practice trials, and the experiment lasted approximately 2 h.

3. Results and discussion

3.1. Benefits of collaboration

Four eyes were better than two. Fig. 2a plots mean reaction times (RT) for correct target present (TP) trials and misses, by condition. When searchers collaborated using only shared voice (SV), targets were detected 1764 ms faster compared to solitary searchers (1P), $t(10) = 2.28$, $p < .05$. Adding shared gaze to speech (SG+V) saved 2151 ms over 1P search, $t(10) = 3.02$, $p < .05$, and 387 ms over SV alone, $t(6) = 0.82$, n.s. However, RTs were fastest with shared gaze alone (SG), a 1154 ms improvement over speech alone (SV), $t(6) = 2.44$, $p = .05$, and an almost two-fold improvement (2918 ms) over 1P, $t(10) = 4.10$, $p < .01$. Strikingly, there was not only a gaze advantage, but a speech cost; searchers using SG were 767 ms faster to find the target than those using SG+V, $t(6) = 5.49$, $p < .01$.

Fig. 2b shows nearly identical patterns for target-absent (TA) RTs. Although RTs did not differ significantly between SV versus 1P or SG+V conditions, $t \leqslant 1.87$, n.s., SG search was faster than 1P, SV, or SG+V search, $t \geqslant 2.63$, $p < .05$. Once again, adding speech to shared gaze introduced a cost, not a benefit, when determining a target's absence.

At first look, the benefits of overt collaboration seem modest compared to the no-communication (NC) baseline; only in the target present SG data were RTs faster, $t(6) = 2.72$, $p = .03$, at a $p = .05$ level of confidence. But these comparisons are compromised due to the near doubling of misses without communication. This evidence for a speed-accuracy tradeoff suggests that searchers prevented from communicating were more prone to compete, despite payoff contingencies. To create a baseline free of this problem, we randomly grouped the eight 1P participants to form four nominal (NOM) pseudo-pairs (taking each trial's response and RT from the faster pseudo-partner). This NOM condition provides a meaningful baseline, as error rates were similar to those in the cooperation conditions (all ps $\geqslant .05$, except for target-absent SG+V). Compared to NOM, TP and TA RTs in the SG condition were significantly faster, $t(6) \geqslant 4.06$, $p < .01$; SG+V RTs were marginally faster, $t(6) \geqslant 2.08$, $p < .10$; and SV RTs were not reliably different, $t(6) \leqslant 0.69$, n.s. These patterns are consistent with a gaze advantage and inconsistent with speech or speech + gaze advantages.

To address how collaborative benefits extend to search efficiency, we analyzed the slopes of the RT × Set Size functions (Fig. 3). Collaborating searchers were roughly twice as efficient as solitary searchers. Search slopes, averaged over TP and TA, were significantly shallower than slopes in the 1P or NOM conditions (all ps $\leqslant .05$). Fig. 4 further quantifies efficiency in terms of fixations. Perfectly efficient collaboration

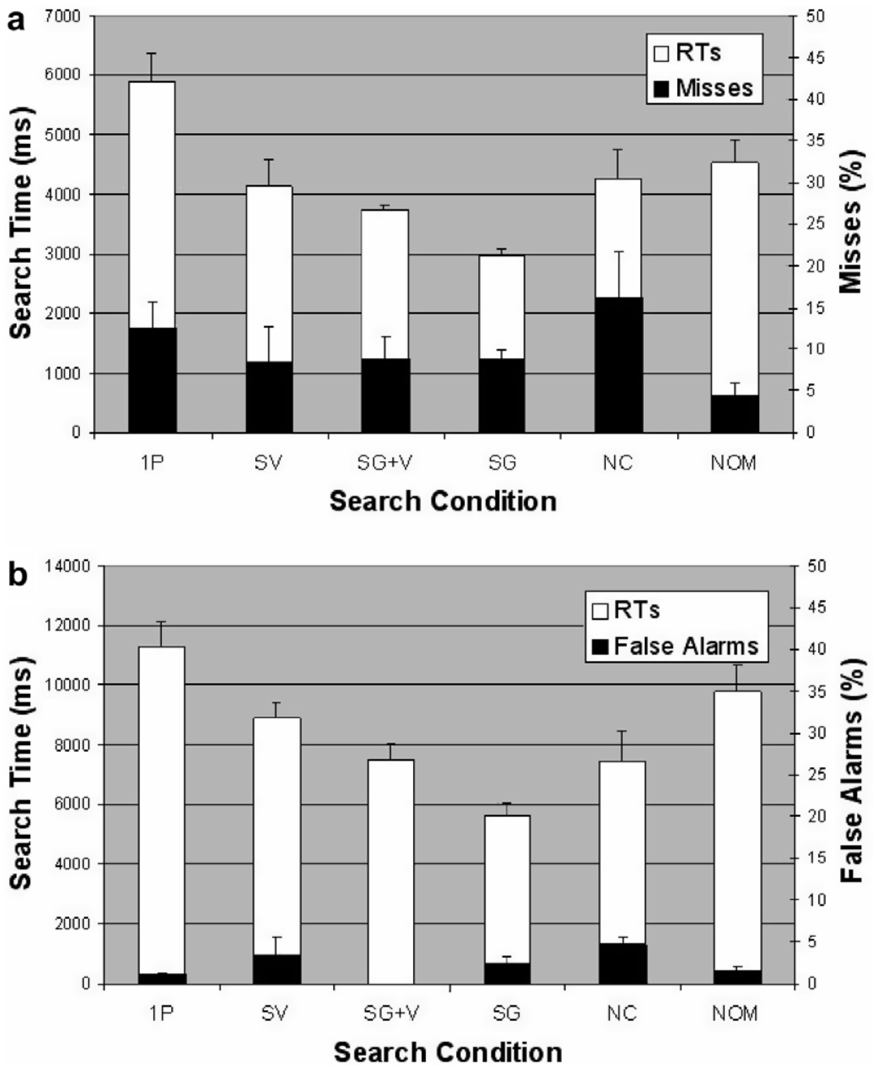

Fig. 2. Manual button-press RTs (left ordinate) and errors (right ordinate) by condition. (a) Target-present data. (b) Target-absent data.

would have the combined fixations from both partners being comparable to the number of fixations by a solitary searcher (with each partner making roughly half the fixations of a solitary searcher). Only SG search attained this optimal level. That SG partners together made no more fixations than solitary searchers (1P, $t(10) \leqslant 0.56$, n.s.; NOM, $t(6) \leqslant 2.09$, n.s.) is strong evidence for the gaze advantage hypothesis.

3.2. Coordination strategies

What coordination strategy underlies this shared gaze advantage? Partners who could communicate typically divided the display, each searching roughly half of

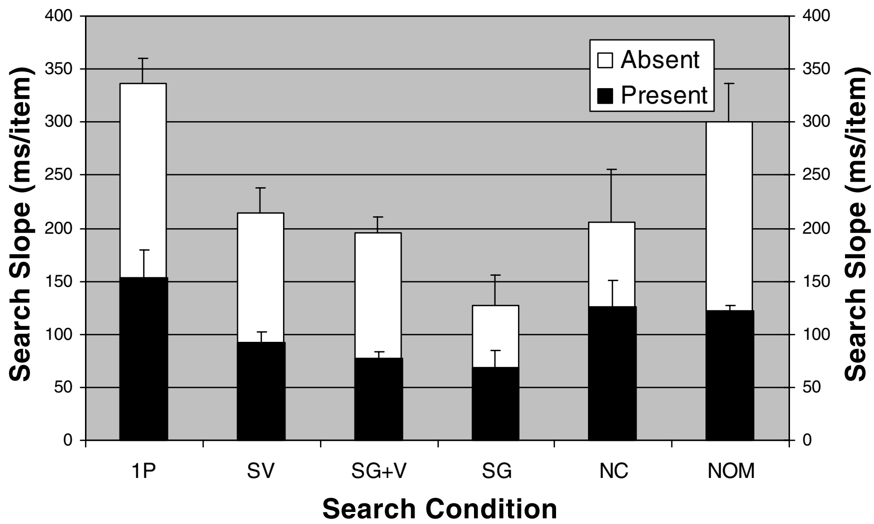

Fig. 3. Search efficiency by condition. Note that SG search was most efficient overall, with slopes in this condition being less than half as steep as those observed for 1P search.

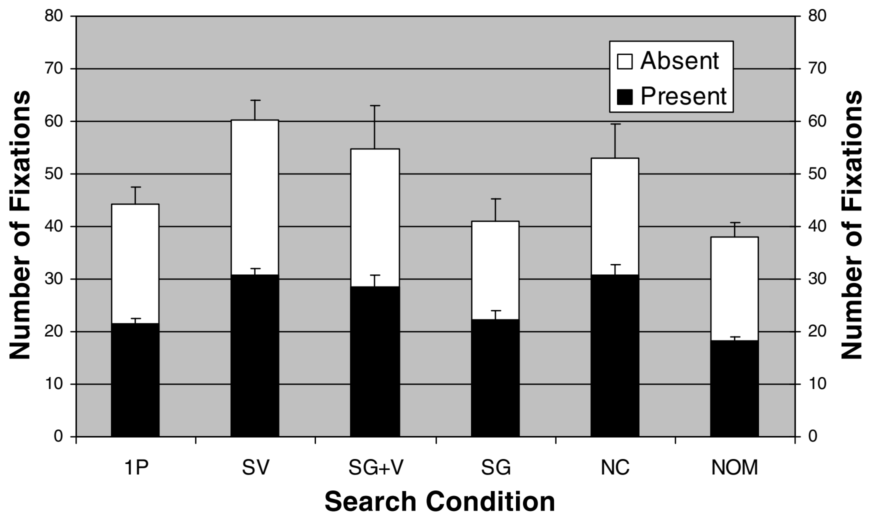

Fig. 4. The average number of fixations made during a search trial by condition. Note that data in the SV, SG+V, SG, and NC conditions include the combined fixations from both searchers. The NOM condition indicates the smaller number of fixations made by either pseudo-partner on a given trial.

the items. Fig. 5 (Panels a–c) presents direct evidence for this *spatial division-of-labor* strategy. Although some pairs chose to divide the display horizontally and others, vertically, they all divided the labor spatially. Moreover, the clear division of fixations suggests that searchers settled on this strategy early on, then used it consistently. Without communication (Panel d), searchers were not able to divide the labor, resulting in overlapping fixation distributions.

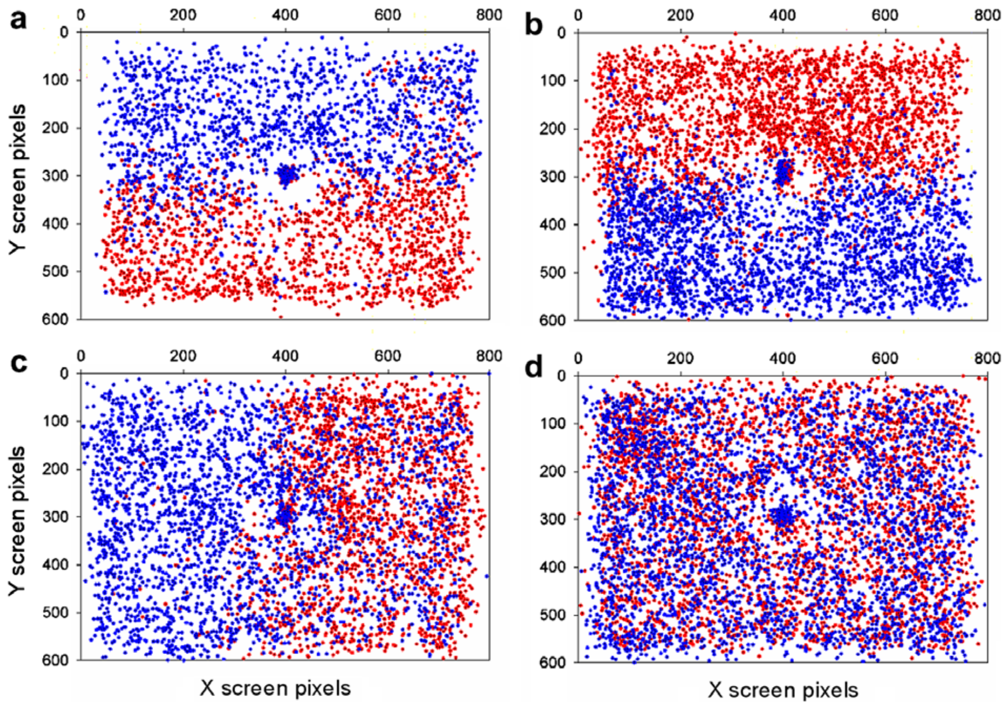

Fig. 5. Fixation distributions from the target-absent trials of one representative searcher pair in the SG (a), SG+V (b), SV (c), and NC (d) conditions. Fixations from searcher A are shown in red, and fixations from searcher B are shown in blue.

To better characterize this division-of-labor strategy, for each trial we calculated the percentages of A's and B's fixations that were in the same display quadrant. Table 1 shows this quadrant overlap analysis aggregated over the experiment, by condition. Compared to NC searchers, communicating searchers (SG, SV, SG+V) were far less likely to fixate in the same display quadrant, $t(6) \geqslant 3.93$, $p < .01$ (averaging TP and TA). This difference was particularly pronounced with SG, which

Table 1
Quadrant overlap by search condition (%)

	Present		Absent	
	21 items	35 items	21 items	35 items
SV	31.3 (1.1)	27.3 (2.2)	55.6 (2.7)	51.3 (2.1)
SG+V	29.3 (2.6)	29.3 (1.3)	48.0 (7.4)	47.7 (7.9)
SG	24.8 (1.7)	22.8 (3.5)	35.8 (3.5)	32.6 (5.7)
NC	51.6 (8.2)	51.9 (6.3)	76.0 (4.9)	74.8 (4.5)

Note: An overlap of 0% would indicate a perfect spatial division of labor in which searchers never looked in the same display quadrant; an overlap of 100% would indicate perfectly redundant search in which searchers looked equally in the same quadrants. Values in parentheses indicate one SEM.

showed less than half the average quadrant overlap found with NC (29% versus 64%, $t(6) = 5.36$, $p = .001$) and significantly less overlap relative to SV, $t(6) = 3.66$, $p = .01$.

Consistent with a spatial division-of-labor strategy and the gaze advantage hypothesis, collaborating searchers avoided redundant effort by segregating their gaze in space. More important, this pattern of data suggests that efficient collaboration entails more than just a one-time decision as to who should inspect which side of the display. Searchers sharing voice alone (SV) also negotiated spatial divisions of labor, yet search in this condition was far less efficient than SG search. As demonstrated by their minimal quadrant overlap, SG searchers coordinated their fixations dynamically, from trial to trial, with a grain of spatial precision not possible with SV. Searchers seemed peripherally aware of where their partner was looking, and were able to use this knowledge to offer targeted search assistance, as exemplified by this SG+V pair's exchange, between-trials:

B: look at you, looking all up on my side
A: 'cause when I finish my side, I check the other side
. . .
B: if you can find it faster than I can, it's all good

Finally, with the exception of SG, $t(6) = 2.00$, n.s., TA overlap was greater than TP overlap, $t(6) \geqslant 2.38$, $p \leqslant .05$, a pattern suggesting ambiguity in when to stop a collaborative TA search, as well as occasional ''partner checking''. That this TA–TP difference was relatively small with SG is another indication that shared gaze is particularly advantageous for coordinating collaborative search.

3.3. The costs of speaking

Adding speech to shared gaze hurt rather than helped performance in this time-critical task. To better understand the nature of speaking costs, we transcribed the speech in the SV and SG+V conditions. Coordination by speaking takes time; the more speaking turns in a given SV or SG+V trial, the slower the response, $r_z = .62$, $p < .001$. Another constraining cost is incurred by the need for politeness. In 37% of SV and 42% of SG+V TP trials, target-finders verbally acknowledged finding targets *before* responding TP. This behavior is consistent with preserving a partner's ''face'' by allowing them options (Brown & Levinson, 1978), manifested here as a need to keep the partner informed. Another aspect of politeness is preserving one's *own* ''face'' (ibid); although speakers commented on 97% of their own errors, this did not introduce much overhead, as most apologies occurred between trials. Without the ability to speak, SG partners in our task were not accountable for such face-management.

All pairs who could speak to one another (SV and SG+V) explicitly discussed dividing the display early on (and all but one did this during practice trials). Higher rates of referring to divisions of the display were correlated with higher error rates for SV searchers, $r = .952$, $p < .05$, but not for SG+V searchers, $r = .453$, n.s.. Moreover, silence was associated with less redundancy for SG+V searchers; pairs who were more often silent were less likely to fixate in the same display quadrant in TA trials, $r = -.98$, $p < .05$. When shared gaze was available, not only did speaking fail to improve coordination, but it incurred a cost.

Finally, absent targets present a challenge for coordination. The partner who responds *target-absent* must either have searched the entire display herself or obtained evidence that her partner has not found the target either. Shared gaze helped in distributing initiative for ending TA trials. Members of SV pairs took more equal initiative, with one member responding TA only seven more times than the other, compared to pairs with shared gaze (SG+V or SG), with one responding TA about 35 more times than the other, $t(12) = 2.69$, $p < .02$. Distributing initiative unequally amounts to specialization; tasks and media that support flexible specialization allow room for optimizing joint activity (e.g., Reed et al., 2006).

4. Conclusions and theoretical implications

Collective behavior is not a simple combination of individual behaviors; the need for coordination qualitatively changes what people do. In this study we manipulated communication mode and monitored eye movements to learn, moment-by-moment, how people spontaneously coordinate collaborative search. We summarize our findings as follows:

(1) *Collaborative search is faster and more efficient than solitary search.* Given that solitary search is already highly efficient, the extent to which any collaboration benefits would offset coordination costs was initially unclear. Not only did we find substantial benefits in this O-in-Qs search task, but also we found that the size of these benefits was nearly optimal when partners communicated by shared gaze alone: Two searchers were virtually twice as good as one.

(2) *People can coordinate collective behavior using shared gaze alone.* Unlike gaze in embodied face-to-face communication, shared gaze cursors are abstractions, albeit precise ones, that don't require triangulating from gazer to object. Perception-of-gaze studies (e.g., Gibson & Pick, 1963; Pusch & Loomis, 2001) focus on how well observers extrapolate the direction of another's gaze, but do not address the question of how gaze is used in interpersonal contexts. Our study produced the first evidence for bi-directional communication between remotely located partners using only gaze cursors. In fact, people spontaneously learned to use this new communication medium without explicit coaching or training, typically within practice trials.

(3) *Shared gaze is highly efficient for mediating collaboration in a spatial task.* Not only were searchers able to communicate using shared gaze, but shared gaze alone proved better for coordinating search than did speech alone. One source of this benefit is the finer-grained spatial division of labor made possible by shared gaze. Whereas searchers limited to speaking divided the display coarsely along the lines of "you look left, I'll look right", shared gaze searchers used a

> "look where I'm not looking" strategy, thereby allowing a more flexible and dynamic division of labor. Searchers could also offer each other targeted assistance, moment-by-moment; if A finished searching her side before B, she would know from B's cursor exactly how to assist his search, and he would know that she was doing so.

Perhaps most remarkable was the speech disadvantage; adding speech to shared gaze produced a cost relative to shared gaze alone. However, speech may well provide benefits in tasks that require consensus or joint decision-making; we leave to future work the question of whether and how partners would use gaze to coordinate more complex tasks (e.g., how long must one partner gaze steadily before this cues the other that a target has been detected?).

Our findings have theoretical implications for visual search. The gaze cursors in our paradigm introduced a nearly continuous stream of sudden visual onsets. If these onsets automatically captured a searcher's attention, thereby diverting processing from searching (Theeuwes, 1994), performance should have been hampered in conditions with SG. This was clearly not the case. Rather, searchers appeared able to covertly attend to a partner's gaze cursor in their visual periphery when they desired this information, then to quickly tune out the cursor while refocusing on the search task. This suggests an ability to dynamically adjust attentional control on a moment-by-moment basis.

There are also implications for communication. We have shown elsewhere (Hanna & Brennan, 2007) that speakers' gaze can provide early disambiguating cues for addressees during face-to-face referential communication. Here, we have shown that sharing abstract representations of gaze enables remote communicators to coordinate on an even finer grain. Our findings also extend the grounding framework, which to date has been useful in explaining how interactional forces and communication media shape utterances in dialogues. Grounding is not limited to coordinating exchanges in which the primary currency is words; our results demonstrate that it can be done entirely non-verbally. Remarkably, people can establish strategies and coordinate joint activity in a visual search task using only shared gaze.

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