32 Collective Intelligence

Thomas W. Malone and Anita Williams Woolley

The other kinds of intelligence described in this book all happen inside a single human brain. But this single-brain intelligence is not the only kind of intelligence on our planet. It would not be surprising to say that animals have intelligence and many people would say that computers also have a kind of (artificial) intelligence. Yet it is surprising to many people to realize that there is another important kind of intelligence on our planet: the *collective intelligence* that arises in *groups* of individuals. For instance, one could say that teams, families, companies, countries, economies, and scientific communities all have different kinds of collective intelligence. And, even though collective stupidity is just as possible as collective intelligence, these collectively intelligent groups are often the most intelligent entities on our planet.

The phenomenon of collective intelligence includes analogies at the group level of many of the aspects of individual intelligence that are described in other chapters of this volume. This way of viewing the world provides an opportunity for applying psychological concepts at a different level and bringing concepts from other fields into psychology.

What Is Collective Intelligence?

As with many important – but evocative – terms, there have been almost as many definitions of collective intelligence as there have been writers who have described it (for a representative list, see Malone & Bernstein, 2015, p. 10). For instance, Hiltz and Turoff (1978) defined collective intelligence as “a collective decision capability [that is] at least as good as or better than any single member of the group” (p. 44). Smith (1994) defined it as “a group of human beings [carrying] out a task as if the group, itself, were a coherent, intelligent organism working with one mind, rather than a collection of independent agents” (p. 1). And Levy (1997) defined it as “a form of *universally distributed intelligence*, constantly enhanced, coordinated in real time, and resulting in the effective mobilization of skills” (p. 13).

Perhaps the simplest – and broadest – definition of collective intelligence comes from Malone and Bernstein (2015):

> *Collective intelligence – groups of individuals acting collectively in ways that seem intelligent.* (p. 3, emphasis in original)

As described by Malone (2018), this definition includes almost all human groups, such as hierarchies, markets, democracies, communities, and ecosystems. This is the definition on which we will focus here and several aspects of this definition are worth noting:

(1) The definition does not try to define "intelligence" itself. Thus, this definition is compatible with all of the other definitions of intelligence in this volume.
(2) By using the word "acting," the definition requires intelligence to be manifested in some kind of behavior. By this definition, for instance, a Wikipedia article would not, itself, be considered intelligent but the group of people who created it would be.
(3) The definition requires that, in order to analyze something as collective intelligence, one must specify a *group* of *individuals* that are involved. In some cases, this may be straightforward, such as noting the individual humans in a company, but, in other cases, it may be useful to draw these boundaries in unusual ways. For instance, one could analyze the collective intelligence of a whole economy by noting that the economy is a collection of many different organizations and people.
(4) The definition requires that the individuals act *collectively*, that is, that there be some connection among their activities. For instance, two unrelated people in two different cities, each making coffee on the same morning, are probably not an example of collective intelligence. But two servers working together to fill all the customer orders in a single coffee shop would be. It is important to note, however, that, even though the individuals' actions need to be connected, the individuals do *not* need to cooperate with each other or have the same goals. For instance, different actors in a market buy and sell things to others in the same market, and thus their actions are connected, but they may each have very different individual goals.
(5) Finally, by using the word "seem," the definition emphasizes that what is considered intelligent depends on the perspective of the observer. For instance, to evaluate whether an entity is acting intelligently, an observer needs to make assumptions about what the entity's goals are. At the individual level, when students take intelligence tests, we assume they are trying to give the answers the test designers consider correct. But if the goal of a student taking the test is to annoy the test-giver, then the test score will not be a good measure of that student's intelligence!

At the level of a group, it is usually even more important for an observer to attribute goals to the group. For instance, when analyzing the collective intelligence of an economy, it is often useful to evaluate how effectively the economy allocates societal resources, even if none of the individuals in the economy has that goal.

History of Studying Collective Intelligence

The earliest scholarly article we have found with the phrase "collective intelligence" in the title was by David Wechsler, the psychologist who developed some of the most widely used IQ tests (Wechsler, 1971). This article argues that collective intelligence is more than just collective behavior in that it involves cross-fertilization resulting in something that could not have been produced by individuals. About this same time, computer scientist Doug Engelbart was doing pioneering work on "augmenting human intellect" with computers, including computational support for team cooperation (Engelbart, 1962, p. 105; Engelbart & English, 1968). Later, Engelbart used the phrase "collective IQ" to describe this work and its broader implications (e.g., Engelbart, 1995).

In 1978, Roxanne Hiltz and Murray Turoff used the term "collective intelligence" to describe the goal of the computerized conferencing systems they pioneered (Hiltz & Turoff, 1978). In the 1980s and 1990s, the term collective intelligence began to be used more and more to describe phenomena from insect behavior (e.g., Franks, 1989) to groups of mobile robots (Mataric, 1993) to human groups (e.g., Atlee & Por, 2000; Isaacs, 1999) to electronically mediated human collaboration (e.g., Heylighen, 1999; Levy, 1997; Smith, 1994). This period also saw early studies using the closely related term "group intelligence" (Williams & Sternberg, 1988).

In the years 2000–2010, the term "collective intelligence" became even more widely used in publications from computer science to spirituality to business (e.g., Hamilton, 2004; Howe, 2008; Szuba, 2001). Of particular importance to the spread of the concept was a bestselling book on *The Wisdom of Crowds* (Surowiecki, 2004) and other books for a general audience featuring the concept of collective intelligence (e.g., Ridley, 2010; Tapscott & Williams, 2006).

This period also saw the first academic conferences on collective intelligence (Bastiaens, Baumol, & Kramer, 2010; Kowalczyk, 2009; Malone & von Ahn, 2012) and the first academic research centers focusing specifically on this topic (Canada Research Chair in Collective Intelligence, University of Ottawa, started in 2002; Center for Collective Intelligence, Massachusetts Institute of Technology (MIT), started in 2006).

In more recent years, an annual conference series on collective intelligence was established (ACM, 2018), a handbook of collective intelligence was published (Malone & Bernstein, 2015), and additional books describing the field for general audiences appeared (Malone, 2018; Mulgan, 2017).

How Does Collective Intelligence Relate to Other Fields?

As we will see in the rest of this chapter, the interdisciplinary field of collective intelligence offers an opportunity to apply concepts from psychology, such as memory, learning, and perception, at the level of groups rather than to individual humans. The field also draws on concepts from other fields, such as economics, sociology, political science, and organization theory, that study groups (see Malone & Bernstein, 2015).

The overlap occurs when there is a focus on overall collective behavior that can be regarded as more or less intelligent. For instance, analyzing how individual people's attitudes are determined or how they make economic choices would not – alone – be central to collective intelligence. But analyzing how different regulatory mechanisms in markets lead to more or less intelligent behavior by the markets as a whole would be central to collective intelligence.

The field of collective intelligence also overlaps with other fields, such as computer science (which uses terms such as crowdsourcing, human computation, and computer-supported cooperative work to study groups of people and computers; Bigham, Bernstein, & Adar, 2015), network science (which studies how aspects of network structure affect the performance of networks; Easley & Kleinberg, 2010), and biology (which studies how groups of animals, such as bees and ants, interact to produce overall behavior that is adaptive for the group; Gordon, 2015).

Elements of Collective Intelligence

One useful way of analyzing collective intelligence is to consider the key elements needed for any group to act intelligently. As Figure 32.1 suggests, we can analyze any intelligent group using four questions: *What* is being done? *Who* is doing it? *Why* are they doing it? And *how* are they doing it? The *how* question can, in turn, be divided into two kinds of processes, *cognitive processes* and *coordination processes*. We will use these categories as an organizing framework for the rest of this chapter.

What

Since the definition of collective intelligence emphasized earlier in this chapter (see the section "What Is Collective Intelligence") leaves intelligence itself undefined, any discussion of collective intelligence requires some – explicit or implicit – definition of intelligence. Even though, as amply illustrated in other

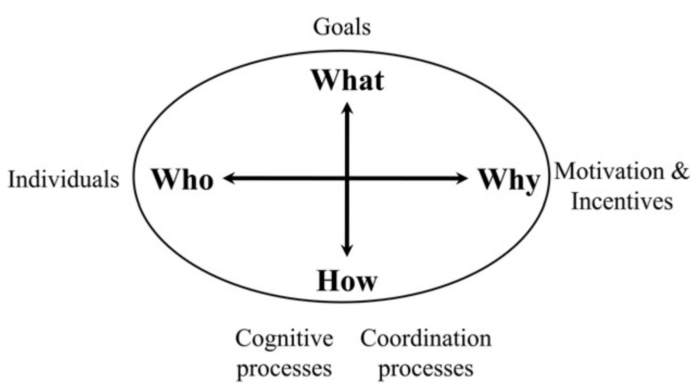

Figure 32.1 *Elements of collectively intelligent systems (after Malone, Laubacher, & Dellarocas, 2010; for a related framework, see Galbraith, 2002).*

chapters of this volume, there are many possible ways to define intelligence, Malone (2018) articulates a useful distinction that is often made implicitly between two broad kinds of intelligence:

- Specialized intelligence – the ability to achieve specific goals effectively in a given environment.
- General intelligence – the ability to achieve a wide range of different goals effectively in different environments. (p. 20)

Using these definitions, specialized intelligence would include, for example, Howard Gardner's definition of intelligence as "the ability to solve problems, or to create products, that are valued within one or more cultural settings" (Gardner, 1983); and general intelligence would include the view of intelligence first identified by Spearman (1904). Spearman called the factor he identified "*g*," for "general intelligence," and this factor is what most modern intelligence tests measure (e.g., Deary, 2000).

These two definitions, in turn, help distinguish two kinds of collective intelligence – *specialized collective intelligence* and *general collective intelligence* – and this provides a useful way of summarizing various results about collective intelligence.

Specialized Collective Intelligence

Much of the literature on teams, organizations, and other groups can be viewed as studies of specialized collective intelligence because it involves groups performing specific tasks. For example, taxonomies of tasks widely used in research and elsewhere have been developed by Steiner (1966, 1972) and McGrath (1984). In these taxonomies, tasks are characterized by the nature of the processes group members must engage in to carry them out effectively (Larson, 2009; McGrath, 1984). For instance, McGrath's task circumplex (1984) identifies four task categories that reflect different sets of team interaction processes: (1) *generate* tasks that require idea generation and divergent thinking; (2) *choose* tasks or decision-making tasks that require selecting among specified alternatives; (3) *negotiate* tasks involving resolution of conflicts of interest or viewpoints; and (4) *execute* tasks involving a high level of coordination, physical movement, or dexterity, to produce a correct or optimal solution.

The type of task a group is faced with has important implications for many other facets of the group to be discussed in the remainder of this chapter, including group composition, incentives, and process.

General Collective Intelligence

It appears that, until recently, no one had asked the question of whether general collective intelligence even exists, that is, whether there is an equivalent of Spearman's *g* for groups: a single statistical factor that predicts how well the group will perform a wide range of tasks. To answer this question, Woolley and colleagues (2010) sampled across the task types described by McGrath (1984) to assess whether groups exhibit a general ability to perform across the full range of different tasks.

In a factor analysis of all the groups' scores, Woolley and colleagues (2010) found that the first factor accounted for 43 percent of the variance in performance on all of the different tasks. This is comparable to the 30–50 percent of variance typically explained by the first factor in a battery of individual cognitive tasks (Chabris, 2007) and suggests the existence of a general collective intelligence factor for groups. Woolley and colleagues (2010) called this factor *c*, by analogy to Spearman's *g*-factor in individual intelligence. This finding has since been replicated in a number of studies and a recent meta-analysis of data from more than 1,000 teams provides further support for the conclusion that a general collective intelligence factor exists in teams (Woolley et al., 2017).

In response to these findings, some have questioned whether the evidence for a general collective intelligence factor is strong enough to conclude that there is a general factor (Credé & Howardson, 2017) as well as whether the factor depends largely on the intelligence of individual team members (Bates & Gupta, 2016). However, the evidence to date supports the conclusion that a general collective intelligence factor exists and suggests opportunities for research to further refine its measurement (Woolley, Kim, & Malone, 2018).

Collective Intelligence and Collective Stupidity

Just as individual humans vary greatly in how intelligent they are, so, too, do groups. Early literature on this topic, for example, often focused on how groups were less intelligent than the individuals in them (e.g., Janis & Mann, 1977; Mackay, 1841) and on the limitations of group decision-making (e.g., Condorcet, 1785/1976). Very recent research has also shown how false stories ("fake news") spread further and faster in social media networks than true ones (Vosoughi, Roy, & Aral, 2018) and many people have speculated that phenomena like this are influencing the outcomes of democratic elections today (e.g., Chakrabarti, 2018).

Yet it has been more common in recent decades to focus on how groups can be smarter than the individuals in them (e.g., Hill, 1982; Surowiecki, 2004). Groups, for instance, can bring more resources to bear on problems (Hill, 1982) and more diversity of perspectives and knowledge (e.g., Page, 2008). Most of the prominent examples of collective stupidity occur when groups block alternative perspectives or bias how those perspectives are considered (e.g., Janis & Mann, 1977); but when groups bring together diverse perspectives and integrate them effectively, the whole can be well more than the sum of the parts (e.g., Bernstein, Shore & Lazer, 2018; Hong & Page, 2004).

Who

The collective intelligence of a group is clearly affected by the characteristics of the group members, that is, by the group composition (e.g., Mann, 1959). Here, we consider three particularly important aspects of group composition: (1) members' *task-relevant abilities*, (2) members' *interpersonal abilities* that help them work together effectively, and (3) the *diversity* of group members on these or other dimensions.

Task-Relevant Abilities

It is clear that, to solve a problem effectively, a group's members should – together – have all the task-relevant knowledge and abilities needed to solve the problem (Hackman, 1987). Research demonstrates, for example, that individual member intelligence maintains a strong relationship with group performance, particularly on specific kinds of tasks, such as decision-making tasks (Devine & Philips, 2001); and Woolley and colleagues (2010) find a moderate correlation between individual intelligence and general collective intelligence. Yet for many teams in a variety of circumstances, task-relevant abilities are necessary but not sufficient for collective intelligence to emerge.

Interpersonal Abilities

Even if a group's members have all the task-relevant knowledge needed, they can still be very ineffective – and thus have very low collective intelligence – if they do not also have the ability to work together well. For instance, there is a general consensus that emotional intelligence (see Chapter 29 in this volume) enhances group performance (Druskat & Wolff, 2001), at least in the short term (Ashkanasy & Daus, 2005). And, even though they did not use these terms, early research by Williams and Sternberg (1988) suggests that when individual group members have other types of intelligence discussed in this volume (such as social intelligence and leadership intelligence) that could increase the performance, and thus the collective intelligence, of a group.

A specific subset of these social intelligence skills, related to the perception of emotions and mental states, has been extensively studied under the term "theory of mind" (ToM; Baron-Cohen et al., 2001; Premack & Woodruff, 1978). A common assumption in much of this research is that people with greater ToM abilities will be more competent at various kinds of social interaction and this has been shown to be true with both children (Watson et al., 1999) and adults (Krych-Appelbaum et al., 2007; Meslec, Aggarwal, & Curşeu, 2016; Woolley et al., 2010).

For instance, Woolley and colleagues (2010) found that groups whose members had higher average ToM scores (as measured by the "Reading the Mind in the Eyes" (RME) Test; Baron-Cohen et al., 2001) also had significantly higher collective intelligence. Indeed, average ToM scores remained the only significant predictor of collective intelligence even when controlling for individual intelligence or other group composition or process variables, such as the proportion of women in the group or the distribution of communication. RME has also predicted performance in teams working together online (Engel et al., 2014) and in groups playing online video games over a period of months (Kim et al., 2017).

Diversity

Diversity of group composition is one of the most commonly studied team variables (e.g., van Knippenberg & Mell, 2016). Despite its potential value, however, a number of studies and meta analyses have failed to show strong effects of diversity on team performance (Joshi & Roh, 2009). Scholars have, therefore, urged researchers to pay close attention to the type of diversity variable studied. It may be critical, for example, to examine the specific type of diversity that is most relevant to the outcomes being investigated (Harrison & Klein, 2007; Horwitz & Horwitz, 2007; Joshi & Roh, 2009; Milliken & Martins, 1996).

With regard to group composition, groups performing tasks that benefit from a range of skills or expertise will underperform unless composed with the requisite cognitive diversity (Woolley et al., 2007; Woolley et al., 2008) even when compared to groups of higher general intelligence or ability (Hong & Page, 2004). Groups that are too homogeneous will also be less creative than more cognitively diverse groups (Aggarwal & Woolley, 2019) and exhibit lower levels of collective intelligence than moderately cognitively diverse groups (Aggarwal et al., 2019). However, groups that are too cognitively diverse run the risk of making costly errors, particularly when the diversity leads them to have difficulties communicating about how to prioritize task elements (Aggarwal & Woolley, 2013). Thus many researchers focus on the moderating effects of group process, such as the development of transactive memory systems and strategic consensus, in examining the relationship between diversity and performance (Aggarwal & Woolley, 2019).

One particularly intriguing kind of diversity in groups comes from using computers, not just to connect group members to each other but as participants in the groups themselves (Kim et al., 2018; Malone, 2018; Weld et al., 2015).

Why

Another key factor in determining the collective intelligence of a group is the motivation of the group members. The literature has generally looked at two sources of motivation – *extrinsic motivation*, often in the form of money or cash incentives, and *intrinsic motivation*, derived from the internal satisfaction associated with the work itself.

Monetary incentives are the core foundation to induce high levels of effort in traditional organizational and market settings (Lazear, 2000; Prendergast, 1999). At times, they have been shown to increase the quantity but not the quality of work produced (Jenkins et al., 1998). The use of group-level monetary incentives can be tricky, as group-based incentives are highly subject to free riding unless accompanied by highly cooperative work behavior (Alchian & Demsetz, 1972; Wageman & Baker, 1997).

When it is difficult to identify and reward the exact contribution made by each worker in a team, the workers will typically lack incentives to provide the optimal level of effort and thus they will work less than if they were working alone. This has also been referred to as the "moral hazard" problem – and suggests that collaboration, particularly by anonymous workers outside of an employment relationship, can produce moral hazard (Holmstrom, 1982) and social loafing (Latane, Williams, & Harkins, 1979). Recommendations for avoiding this include making individual contributions identifiable and encouraging intrinsic motivation by making the work personally meaningful (Benkler, Shaw, and Hill, 2015; Deci & Ryan, 1985; Hackman & Oldham, 1976).

How – Cognitive Processes

The key cognitive processes needed for collective intelligence are those that are needed for any kind of intelligent system, whether it is a human, a machine, or a group. One useful way of classifying these processes is shown in Figure 32.2. Working backward from the action an intelligent system takes, the figure shows that to act effectively in the world, the system needs to *decide* what action to take. To do this, the system needs to somehow *create* possible options for action. This combination of creating and deciding can be called problem-solving, and to do effective problem-solving a system usually needs to also *sense* the external world and *remember* relevant information. Finally, to do all these things better over time, the system needs to *learn* from its own experience. We'll consider the different cognitive processes in this order, emphasizing results from social and organizational psychology but also including selected examples from other disciplines.

Decide

The ability of groups to make decisions effectively – that is, to share relevant details, weight information appropriately, and arrive at the best decision – is directly tied to team performance (Mesmer-Magnus & DeChurch, 2009). For instance, groups frequently fail to surface relevant information and combine it appropriately; instead, they disregard relevant information while basing their decisions on irrelevant

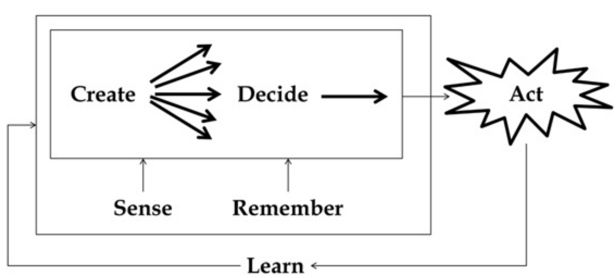

Figure 32.2 *Cognitive processes used by intelligent systems (from Malone, 2018).*

information (Larson, 2009). This can occur as a result of cognitive factors, motivational factors, or as a consequence of bad process.

Cognitive factors. A long line of work on social decision schemes has investigated how predecision preferences of individuals combine to influence a joint decision (Davis, 1973). Groups are also more likely than individual decision-makers to use certain cognitive heuristics and biases (Kerr, MacCoun, & Kramer, 1996). For instance, when there are "hidden profiles," in which members initially prefer different alternatives based on conflicting information they hold, they may need to make a special effort to surface and share all the information they need to reach the correct solution (Stasser & Titus, 1985).

Motivational factors. Motivational approaches to group decision-making focus on group members' motivation to share the information they have, to overlook disconfirming evidence, and to believe in the infallibility of their own group. For instance, work on groupthink, social comparison, and intragroup competition examines various aspects of these motivational issues (Isenberg, 1986; Janis & Mann, 1977; Sanders & Baron, 1977; Toma and Butera, 2009).

Process design factors. The benefits of using collections of *independent* decision-makers have been repeatedly shown in studies where the average of many individuals' estimates is often closer to the true value than almost all of the individual guesses (Galton, 1907; Surowiecki, 2004). However, for this to happen, the individual estimates must be independent of one another and the sample sufficiently large and unbiased to enable errors to be symmetrically distributed (Steyvers & Miller, 2015; Surowiecki, 2004). Even subtle social influence revealing knowledge of others' estimates can create a cascade of effects that reduces the accuracy of crowds (Lorenz et al., 2011).

While independent decision-makers can be useful for some types of decisions, interacting groups are often better when the options are not well defined or when the group needs to buy into a decision for it to be implemented. In these circumstances, outcomes can often be improved by having the group identify key questions to be answered and how to integrate their information to answer those questions (i.e., Woolley et al., 2008).

Another type of intervention involves encouraging a group to grant equal speaking time to all group members on the assumption that this will enable more relevant facts to be brought into the discussion. Equality in speaking time has been associated with higher collective intelligence in groups (Engel et al., 2014; Woolley et al., 2010) and interventions involving real-time feedback on relative contributions to group conversation have also been shown to improve group decision-making performance (DiMicco, Pandolfo, & Bender, 2004).

More generally, there are many ways to organize group decision-making processes beyond the types typically studied by psychologists. For example, Malone (2018) identifies five common types of group decision-making processes as reflected across a number of disciplines: *hierarchies* (in which decisions are made by those with delegated authority), *democracies* (in which decisions are made by voting), *markets* (in which decisions are made by pairwise agreements between buyers and sellers), *communities* (in which decisions are made by informal consensus based on shared norms and reputations), and *ecosystems* (in which decisions are made based on power: the law of the jungle and survival of the fittest).

We believe there are interesting research opportunities to systematically study and compare all these different group decision-making methods both empirically and analytically. Economists, for instance, have shown mathematically that the combination of pairwise agreements between buyers and sellers in markets leads, in specified conditions, to overall group decisions about how resources are allocated that are optimal, in the sense that there is no way they could be improved without making at least some individuals worse off (Arrow & Debreu, 1954; Lo, 2015). And much recent work in behavioral economics has focused on the empirical study of how actual human decision-making departs from the ideal of completely rational decision-making that is assumed by most traditional economic models (e.g., Brennan and Lo, 2012; Camerer, Loewenstein, and Rabin, 2004; Kahneman & Tversky, 1979). What analogous kinds of work could be done for the other group decision-making processes listed above and for comparisons among them?

Create

To make a decision, a group needs to create (implicitly or explicitly) options from which to choose. An effective process for "creating" often involves engaging in divergent thought, where group members bring in as wide a variety of options as possible. However, research on group creativity has repeatedly found that, on average, groups perform worse on brainstorming tasks than nominal groups with the same number of individuals (Girotra, Terwiesch, & Ulrich, 2010; Stroebe, Nijstad, & Rietzschel, 2010). Subsequent research has found, however, that altering the structure of a brainstorming group can enhance creative performance (Girotra, Terwiesch, & Ulrich, 2010; Korde & Paulus, 2017). For instance, early work on the hybrid group format in brainstorming overcomes group process obstacles (i.e., production blocking, social loafing, evaluation apprehension) by employing an individual phase prior to the group phase (Girotra, Terwiesch, & Ulrich, 2010; Larson, 2009; Stroebe, Nijstad, & Rietzschel, 2010).

In addition to small group creativity studies like these, it is important to realize that these sorts of divergent processes underlie creation in larger collectives as well. For instance, product design groups in hierarchical companies delegate different parts of the design process to different individuals and teams (Ulrich & Eppinger, 2015) and markets allow different companies to develop different options from which buyers collectively choose the options that will succeed.

Sense

In order to create and decide intelligently, groups usually need to sense their environment. This happens, for example, when a medical treatment team diagnoses a patient's condition, when voters in a democracy see news stories about what politicians say, and when governments collect and analyze information to assess whether a foreign nation is developing biological weapons. These processes of collective sensing have been less studied by researchers than deciding and creating; but one of the main terms researchers have used to study them is *sensemaking* (Pirolli & Russell, 2011; Weick, 1995; Weick, Sutcliffe, & Obstfeld, 2005) For example, Weick (1993) uses this perspective to analyze a famous disaster in which thirteen members of a firefighting crew died, in part because their expectations that they were fighting a small and easily controlled fire led them to misinterpret what they were seeing. In general, the careful structuring of collective attention lays the groundwork for collectives to notice and respond to critical issues, or to overlook, miss, and underestimate them (Hackman, 2011; Ocasio, 1997).

Even though the allocation of *attention* plays a role in all the cognitive processes, it is central to sensing the environment and determining what stimuli or events require response. Work on attention at the organizational level started with Simon (1947) who examined the channeling, structuring, and allocation of attention as a central concept in studying administrative behavior. Ocasio (1997), in his attention-based theory of the firm, focused on how attention in organizations shapes organizational adaptation. Newer lines of work examine "attentional selection," the development of shared attention in groups (Ocasio, 2011), and ask: What do collectives make the center of their focus? And what do they allow to fall by the wayside?

For instance, teams that focus on *outcomes* tend to produce more innovative or creative outcomes and adapt more effectively to difficulties that arise in their work (Woolley, 2009a, 2009b), while teams that focus on *processes* commit fewer errors (Aggarwal & Woolley, 2013). In other words, where teams focus their attention leads them to sense different issues (while ignoring others) and respond differently. And the degree to which group members agree about the team's strategic priorities can strongly affect how creative they are and the quality of the team's outcomes (Aggarwal & Woolley, 2013, 2019).

Remember

Groups remember things in a variety of ways: in their written records and online systems, in their habitual organizational routines (Nelson & Winter, 1982), in their group norms, and, of course, in the minds of their members. One useful way of thinking about how a group's memory emerges from the individual memories of its members is called transactive memory systems (Wegner, 1987). A transactive memory system (TMS) refers to a shared system that individuals in groups develop to collectively encode, store, and retrieve information or knowledge in different domains (Argote & Ren, 2012; Hollingshead, 2001; Lewis & Herndon, 2011). Groups with a well-developed TMS can efficiently store and make use of a broader range of knowledge than groups without an effective TMS. According to TMS theory, there are three behavioral indicators of an effective TMS: *specialization, credibility*, and *coordination* (Lewis, 2004).

Through performing tasks and answering questions, a member establishes credibility and expertise status. Other members, being aware of the person's expertise, direct new knowledge in the domain to him or her, which reinforces the person's specialization and team members' trust in his or her expertise. Further, members know whom to count on for performing various tasks and whom to consult for information in particular domains, which improves coordination (Argote & Ren, 2012). Dozens of studies have demonstrated the positive effects of TMS on group performance in both laboratory and field settings (Lewis & Herndon, 2011), though work continues to refine measures and conceptualization of the construct and its relationship to performance for different types of tasks (Lewis & Herndon, 2011).

Learn

A great deal of evidence suggests that groups and organizations vary enormously in their ability to learn. The performance of some organizations improves dramatically with experience while the performance of others remains unchanged or even deteriorates (Argote, 1999).

In general, group learning refers to changes in a group – including changes in cognitions, routines, or performance – that occur as a function of experience (Argote & Miron-Spektor, 2011; Fiol & Lyles, 1985). For example, as groups gain experience, they may acquire information about which group members are good at which tasks, how to use a new piece of technology more effectively, or how to coordinate their activities better. This knowledge may in turn improve their performance (Argote, 1999).

It is sometimes useful to distinguish between two kinds of group learning: (1) changes in *knowledge* (which may be gauged from change in performance) and (2) changes in *group processes* or repertoires (Argote & Miron-Spektor, 2011; Edmondson, 1999; Fiol & Lyles, 1985; Wilson, Goodman, & Cronin, 2007). It is also important to realize that groups may learn (e.g., change processes) without any change in performance and they may change performance (e.g., because of changes in the environment) without any corresponding change in the group's knowledge (Argote, 1999). And sometimes knowledge may be *explicit* (easily codifiable and observable; Kogut & Zander, 1992) while at other times it may be only *tacit* (unarticulated and difficult to communicate; Nonaka, 1994).

An organization's overall ability to learn productively – that is, to improve its outcomes through better knowledge and insight (Fiol & Lyles, 1985) – depends on the ability of its teams to learn (Edmondson, 1999; Roloff, Woolley, & Edmondson, 2011; Senge & Sterman, 1992). Much of the work on group learning uses the concept of learning curves originally developed in individual psychology (Ebbinghaus, 1885; Thorndike, 1898) to characterize the rate of improvement and researchers have found considerable variation in this rate for different groups (Argote & Epple, 1990; Dutton & Thomas, 1984; Knott, 2008).

In addition to hierarchical organizations, of course, learning also occurs in other kinds of collectively intelligent groups. Markets, for example, learn as sellers continually try to provide products that will be more desirable to customers than their competitors' products and the sellers that fail to do this well go out of business. At an even more general level, different kinds of collectively intelligent systems are always competing with each other for power and survival in the ecosystem of collectively intelligent systems (Malone, 2018, chap. 10).

How – Coordination Processes

Whenever activities are carried out by a group of individuals instead of a single individual, the individuals' activities need to somehow be coordinated with each other. This coordination can usefully be viewed as managing interdependencies among activities (Faraj & Xiao, 2006; Malone, Laubacher, & Dellarocas, 2010; Okhuysen & Bechky, 2009).

For instance, Thompson (1967) identified three types of interdependencies among activities: *pooled* (where, for instance, activities share a resource such as money or machine time), *sequential* (where resources from one activity flow to another one), and *reciprocal* (where resources flow back and forth between two or more activities). Thompson and later researchers (Malone et al., 1999; Van de Ven, Delbecq, & Koenig, 1976) showed how different kinds of coordination processes are appropriate for different kinds of interdependencies. For instance, pooled (or "shared resource") dependencies can be managed by coordination processes such as "first come-first served," priority order, budgets, managerial decision, or market-like bidding (Malone et al., 1999).

More generally, each of the different types of decision-making structures discussed by Malone (2018) has different implications for how activities can be coordinated in systems that use them. For instance, effective hierarchies usually need to *differentiate*, that is, to divide the overall goal of the organization into different tasks done by different subgroups and also to *integrate* the different subgroups using mechanisms such as informal communication and integrating managers (Galbraith, 2002; Lawrence & Lorsch, 1967).

It is also important to realize that the coordination processes associated with the different decision-making methods have different advantages and disadvantages (Malone, 2018, chap. 11). For instance, organizational theorists and economists have analyzed how the choice of whether it is better to organize activities using hierarchies or markets depends on factors like the transaction costs and incompleteness of contracts under the different arrangements (Hart, 1995; Williamson, 1973, 1981). And new information technologies, by changing the costs of coordination and other activities, can change these tradeoffs and enable new forms of organizational coordination (Malone, 2004; Malone, Yates, & Benjamin, 1987; Malone, Laubacher, & Dellarocas, 2010).

Conclusions

Just as studying the neural basis for intelligence provides a link between cognitive psychology and lower level neural processes, studying collective intelligence provides a link between cognitive psychology and higher-level social, organizational, and economic processes. We have summarized here some of the work so far on these topics and we believe there are substantial opportunities for further research in this area. To the degree that we can better understand the collectively intelligent groups that surround us all the time, we may also be better able to design and use them for solving our most important problems.

Acknowledgments

The work reported in this chapter has been supported by several sponsors over the years, including the US National Science Foundation (grant numbers IIS-0963285, ACI-1322254, IIS-0963451, IIS-1442887, IIS-1047567), the US Army Research Office (grant numbers 56692-MA, 64079-NS, W911NF-15–1-0577, and W911NF-13–1-0422), and other sponsors of the MIT Center for Collective Intelligence.

Portions of this chapter appeared previously in the chapters titled "Introduction," "Collective intelligence in teams and organizations," and "Conclusion" in T. W. Malone and M. S. Bernstein (Eds.) (2015), *Handbook of Collective Intelligence.* Cambridge, MA: MIT Press (copyright © 2015 Massachusetts Institute of Technology).

References

ACM (Association for Computing Machinery). (2018). Collective Intelligence Conference Series. https://ci.acm.org/

Aggarwal, I., & Woolley, A. W. (2013). Do you see what I see? The effect of members' cognitive styles on team processes and performance. *Organizational Behavior and Human Decision Processes*, *122*, 92–99.

Aggarwal, I., & Woolley, A. W. (2019). Team creativity, cognition, and cognitive style diversity. *Management Science*, *64*(4), 1586–1599. https://doi.org/10.1287/mnsc.2017.3001

Aggarwal, I., Woolley, A. W., Chabris, C. F., & Malone, T. W. (2019). The impact of cognitive style diversity on implicit learning in teams. *Frontiers in Psychology*, (*10*), 112. https://doi.org/doi: 0.3389/fpsyg.2019.00112

Alchian, A. A., & Demsetz, H. (1972). Production, information costs, and economic organization. *The American Economic Review*, *62*(5), 777–795.

Argote, L. (1999). *Organizational learning: Creating, retaining, and transferring knowledge*. Norwell, MA: Kluwer Academic.

Argote, L., & Epple, D. (1990). Learning curves in manufacturing. *Science*, *247*, 920–924.

Argote, L., & Miron-Spektor, E. (2011). Organizational learning: From experience to knowledge. *Organization Science*, *22*(5), 1123–1137.

Argote, L., & Ren, Y. (2012). Transactive memory systems: A microfoundation of dynamic capabilities. *Journal of Management Studies*, *49*(8), 1375–1382.

Arrow, K. J., & Debreu, G. (1954). Existence of an equilibrium for a competitive economy. *Econometrica*, *22*, 265–290.

Ashkanasy, N. M., & Daus, C. S. (2005). Rumors of the death of emotional intelligence in organizational behavior are vastly exaggerated. *Journal of Organizational Behavior*, *26*(4), 441–452.

Atlee, T., & Por, G. (2000). Collective intelligence as a field of multi-disciplinary study and practice. www.academia.edu/1981875/Collective_Intelligence_as_a_Field_of_Multi-disciplinary_Study_and_Practice

Baron-Cohen, S., Wheelwright, S., Hill, J., Raste, Y., & Plumb, I. (2001). The "Reading the Mind in the Eyes" Test revised version: A study with normal adults, and adults with Asperger syndrome or high-functioning autism. *The Journal of Child Psychology and Psychiatry and Allied Disciplines*, *42*(2), 241–251.

Bastiaens, T. J., Baumol, U., & Kramer, B. J. (Eds.). (2010). On collective intelligence. In *Proceedings of the Symposium on Collective Intelligence, Hagen, Germany, April 15–16, 2010*. Berlin: Springer-Verlag.

Bates, T. C., & Gupta, S. (2016). Smart groups of smart people: Evidence for IQ as the origin of collective intelligence in the performance of human groups. *Intelligence*, 60, 46–56.

Benkler, Y., Shaw, A., & Hill, B. M. (2015). Peer production: A form of collective intelligence. In T. W. Malone & M. S. Bernstein (Eds.), *Handbook of collective intelligence*. Cambridge, MA: MIT Press.

Bernstein, E., Shore, J., & Lazer, D. (2018). How intermittent breaks in interaction improve collective intelligence. *Proceedings of the National Academy of Sciences*, *115*(35), 8734–8739.

Bigham, J. P., Bernstein, M. S., & Adar, E. (2015). Human-computer interaction and collective intelligence. In T. W. Malone & M. S. Bernstein (Eds.), *Handbook of collective intelligence*. Cambridge, MA: MIT Press.

Brennan, T. J., & Lo, A. W. (2012). An evolutionary model of bounded rationality and intelligence, *PLoS One*, *7*, e50310. doi:10.1371/journal.pone.0050310.

Camerer, C. F., Loewenstein, G., & Rabin, M. (Eds.) (2004). *Advances in Behavioral Economics*. Princeton: Princeton University Press.

Chabris, C. F. (2007). Cognitive and neurobiological mechanisms of the law of general intelligence. In M. J. Roberts (Ed.), *Integrating the mind: Domain general versus domain specific processes in higher cognition* (pp. 449–491). Hove: Psychology Press.

Chakrabarti, S. (2018). Hard questions: What effect does social media have on democracy? *Facebook Newsroom*, January 22. https://newsroom.fb.com/news/2018/01/effect-social-media-democracy/.

Condorcet, M. (1785/1976). Essay on the application of analysis to the probability of majority decisions. In K. M. Baker (Ed.), *Condorcet: Selected writings*, Indianapolis, IN: Bobbs-Merrill.

Credé, M., & Howardson, G. (2017). The structure of group task performance: A second look at "collective intelligence": Comment on Woolley et al. (2010), *Journal of Applied Psychology*, *102*(10), 1483–1492.

Davis, J. H. (1973). Group decision and social interaction: A theory of social decision schemes. *Psychological Review*, *80*(2), 97–125.

Deary, I. J. (2000). *Looking down on human intelligence: From psychometrics to the brain*. New York: Oxford University Press.

Deci, E. L., & Ryan, R. M. (1985). *Intrinsic motivation and self-determination in human behavior*. New York: Plenum Press.

Devine, D. J., & Philips, J. L. (2001). Do smarter teams do better? A meta-analysis of cognitive ability and team performance. *Small Group Research*, *32*(5), 507–532.

DiMicco, J. M., Pandolfo, A., & Bender, W. (2004). Influencing group participation with a shared display. In *Proceedings of the 2004 ACM conference on Computer supported cooperative work* (pp. 614–623). New York: Association for Computing Machinery.

Druskat, V. U., & Wolff, S. B. (2001). Building the emotional intelligence of groups. *Harvard Business Review*, *79*(3), 80–90.

Dutton, J. M., & Thomas, A. (1984). Treating progress functions as a managerial opportunity. *Academy of Management Review*, *9*, 235–247.

Easley, D., & Kleinberg, J. (2010). *Networks, crowds, and markets: Reasoning about a highly connected world*. Cambridge: Cambridge University Press.

Ebbinghaus, H. (1885). *Memory: A contribution to experimental psychology*. New York: Dover Publications.

Edmondson, A. (1999). Psychological safety and learning behavior in work teams. *Administrative Science Quarterly*, *44*(2), 350–383.

Engel, D., Woolley, A. W., Jing, L. X., Chabris, C. F., & Malone, T. W. (2014). Reading the mind in the eyes or reading between the lines? Theory of mind predicts collective intelligence equally well online and face-to-face. *PLoS One*, *9*(12), e115212.

Engelbart, D. C. (1962). *Augmenting human intellect: A conceptual framework*. No. Summary Report AFOSR-3223 under Contract AF 49 (638)-1024, SRI Project 3578 for Air Force Office of Scientific Research, Stanford Research Institute.

Engelbart, D. C. (1995). Toward augmenting the human intellect and boosting our collective IQ. *Communications of the ACM*, *38*(8), 30–32.

Engelbart, D. C., & English, W. K. (1968). A research center for augmenting human intellect. In *Proceedings of the December 9–11,1968, Fall Joint Computer Conference* (Vol. 33, pp. 395–410). San Francisco: Association for Computing Machinery.

Faraj, S., & Xiao, Y. (2006). Coordination in fast-response organizations. *Management Science*, *52*(8), 1155–1169.

Fiol, C. M., & Lyles, M. A. (1985). Organizational learning. *Academy of Management Review*, *10*(4), 803–813.

Franks, N. R. (1989). Army ants: A collective intelligence? *American Scientist*, *7*(2), 138–145.

Galbraith, J. R. (2002). *Designing organizations*. San Francisco: Jossey-Bass.

Galton, F. (1907). Vox Populi. *Nature*, *75*(7), 450–451.

Gardner, H. (1983). *Frames of mind: The theory of multiple intelligences*. New York: Basic books.

Girotra, K., Terwiesch, C., & Ulrich, K. T. (2010). Idea generation and the quality of the best idea. *Management Science*, *56*(4), 591–605.

Gordon, D. M. (2015). Collective behavior in animals: An ecological perspective. In T. W. Malone & M. S. Bernstein (Eds.), *Handbook of collective intelligence*. Cambridge, MA: MIT Press.

Hackman, J. R. (1987). The design of work teams. In J. W. Lorsch (Ed.), *Handbook of organizational behavior* (pp. 315–342). Englewood Cliffs, NJ: Prentice Hall.

Hackman, J. R. (2011). *Collaborative intelligence: Using teams to solve hard problems*. San Francisco: Berrett-Koehler Publishers.

Hackman, J. R., & Oldham, G. R. (1976). Motivation through the design of work: Test of a theory. *Organizational Behavior and Human Decision Processes*, *16*(2), 250–279.

Hamilton, C. (2004). Come together: Can we discover a depth of wisdom far beyond what is available to individuals alone? What Is Enlightenment, May–July, 57–77.

Harrison, D. D., & Klein, K. J. (2007). What's the difference? Diversity constructs as separation, variety, or disparity in organizations. *Academy of Management Review*, *32*(4), 1199–1228.

Hart, O. (1995). *Firms, contracts, and financial structure*. London: Oxford University Press.

Heylighen, F. (1999). Collective Intelligence and its implementation on the Web: Algorithms to develop a collective mental map. *Computational and Mathematical Organization Theory*, *5*(3), 253–280.

Hill, G.W. (1982). Group versus individual performance: Are N + 1 heads better than one? *Psychological Bulletin*, *91*, 517–539.

Hiltz, S. R., & Turoff, M. (1978). *The network nation: Human communication via computer*. Reading, MA: Addison-Wesley.

Hollingshead, A. B. (2001). Cognitive interdependence and convergent expectations in transactive memory. *Journal of Personality and Social Psychology*, *81*(6), 1080–1089.

Holmstrom, B. (1982). Moral hazard in teams. *The Bell Journal of Economics*, *13*(2), 324–340.

Hong, L., & Page, S. E. (2004). Groups of diverse problem solvers can outperform groups of high-ability problem solvers. *Proceedings of the National Academy of Sciences*, *101* (46), 16385–16389.

Horwitz, S. K., & Horwitz, I. B. (2007). The effects of team diversity on team outcomes: A meta-analytic review of team demography. *Journal of Management*, *33*(6), 987–1015.

Howe, J. (2008). *Crowdsourcing: How the power of the crowd is driving the future of business*. New York: Three Rivers Press.

Isenberg, D. J. (1986). Group polarization: A critical review and meta-analysis. *Journal of Personality and Social Psychology*, *50*(6), 1141–1151.

Isaacs, W. (1999). *Dialogue and the art of thinking together*. New York: Doubleday Currency.

Janis, I. L., & Mann, L. (1977). *Decision making: A psychological analysis of conflict, choice, and commitment*. New York, NY: Free Press.

Jenkins, G. D., Mitra, A., Gupta, N., & Shaw, J. D. (1998). Are financial incentives related to performance? A meta-analytic review of empirical research. *Journal of Applied Psychology*, *83*(5), 777–787.

Joshi, A., & Roh, H. (2009). The role of context in work team diversity research: A meta-analytic review. *Academy of Management Journal*, *52*(3), 599–627.

Kahneman, D., & Tversky, A. (1979). Prospect theory: An analysis of decision and risk. *Econometrica*, *47*(2), 263–291.

Kerr, N. L., MacCoun, R. J., & Kramer, G. P. (1996). Bias in judgment: Comparing individuals and groups. *Psychological Review*, *103*(4), 687–719.

Kim, Y. J., Engel, D., Woolley, A., Lin, J., McArthur, N., & Malone, T. W. (2017). What makes a strong team? Using collective intelligence to predict performance of teams in League of Legends. In *Proceedings of the 20th ACM conference on computer-supported cooperative work and social computing (CSCW 2017)* (pp. 2316–2329). New York: Association for Computing Machinery.

Kim, Y. J., Gupta, P., Glikson, E., Woolley, A.W., & Malone, T. W. (2018). Enhancing collective of human-machine teams. Paper presented at the ACM Conference on Collective Intelligence, Zurich, Switzerland, July 7–8.

Knott, A. M. (2008). R&D/returns causality: Absorptive capacity or organizational IQ. *Management Science*, *54*(12), 2054–2067.

Kogut, B., & Zander, U. (1992). Knowledge of the firm, combinative capabilities, and the replication of technology. *Organization Science*, *3*(3), 383–397.

Korde, R., & Paulus, P. B. (2017). Alternating individual and group idea generation: Finding the elusive synergy. *Journal of Experimental Social Psychology*, *70*, 177–190.

Kowalczyk, R. (Ed.). (2009). Computational collective intelligence. Paper presented at the Proceedings of the First International Conference on Computational Collective Intelligence, Wroclaw, Poland, October 5–7.

Krych-Appelbaum, M., Law, J. B., Barnacz, A., Johnson, A., & Keenan, J. P. (2007). The role of theory of mind in communication. *Journal of Interaction Studies*, *8*(2), 267–280.

Larson, J. R. (2009). *In search of synergy in small group performance*. New York: Psychology Press.

Latane, B., Williams, K., & Harkins, S. (1979). Many hands make light the work: The causes and consequences of social loafing. *Journal of Personality and Social Psychology*, *37*(6), 822–832.

Lawrence, P. R., & Lorsch, J. W. (1967). *Organization and environment: Managing differentiation and integration*. Cambridge, MA: Harvard Business School Press.

Lazear, E. P. (2000). Performance pay and productivity. *The American Economic Review*, *90* (5), 1346–1361.

Levy, P. (1997). *Collective intelligence: Mankind's emerging world in cyberspace*. New York: Plenum Press.

Lewis, K. (2004). Knowledge and performance in knowledge-worker teams: A longitudinal study of transactive memory systems. *Management Science*, *50*, 1519–1533.

Lewis, K., & Herndon, B. (2011). The relevance of transactive memory systems for complex, dynamic group tasks. *Organization Science*, *22*(5), 1254–1265.

Lo, A. (2015). The wisdom of crowds vs. the madness of mobs. In T. W. Malone & M. S. Bernstein (Eds.), *Handbook of collective intelligence*. Cambridge, MA: MIT Press.

Lorenz, J., Rauhut, H., Schweitzer, F., & Helbing, D. (2011). How social influence can undermine the wisdom of crowd effect. *Proceedings of the National Academy of Sciences*, *108*(22), 9020–9025. https://doi.org/10.1073/pnas.1008636108.

Mackay, C. (1841). *Memoirs of extraordinary popular delusions and the madness of crowds* (1st ed.). London: Richard Bentley.

Malone, T. W. (2004). *The future of work: How the new order of business will shape your organization, your management style and your life*. Boston: Harvard Business School Press.

Malone, T. W. (2018). *Superminds: The surprising power of people and computers thinking together*. Boston: Little, Brown and Company.

Malone, T. W., & Bernstein, M. S. (2015). Introduction. In T. W. Malone & M. S. Bernstein (Eds.), *Handbook of collective intelligence*. Cambridge, MA: MIT Press.

Malone, T. W., Crowston, K., Lee, J., Pentland, B., Dellarocas, C., Wyner, G., et al. (1999). Tools for inventing organizations: Toward a handbook of organizational processes. *Management Science*, *45*(3), 425–443.

Malone, T. W., Laubacher, R., & Dellarocas, C. (2010). The collective intelligence genome. *MIT Sloan Management Review*, *51*(3), 21–31.

Malone, T. W., & von Ahn, L. (2012). *Proceedings of the Collective Intelligence 2012 Conference*. Cambridge, MA. http://arxiv.org/abs/1204.2991v3

Malone, T. W., Yates, J., & Benjamin, R. I. (1987). Electronic markets and electronic hierarchies. *Communications of the ACM*, *30*(6), 484–497.

Mann, R. D. (1959). A review of the relationships between personality and performance in small groups. *Psychological Bulletin*, *56*(4), 241–270. https://doi.org/10.1037/h0044587

Mataric, M. J. (1993). Designing emergent behaviors: From local interactions to collective intelligence. In A. Meyer, H. Roitblat, & S. Wilson (Eds.), *Proceedings of the Second International Conference on Simulation of Adaptive Behavior* (pp. 432–441). Cambridge, MA: MIT Press.

McGrath, J. E. (1984). *Groups: Interaction and performance*. Englewood Cliffs, NJ: Prentice-Hall.

Meslec, N., Aggarwal, I., & Curşeu, P. L. (2016). The insensitive ruins it all: Compositional and compilational influences of social sensitivity on collective intelligence in groups. *Frontiers in Psychology*, 7, 676. https://doi.org/10:3389/fpsyg.2016.00676

Mesmer-Magnus, J. R., & DeChurch, L. A. (2009). Information sharing and team performance: A meta-analysis. *Journal of Applied Psychology*, *94*(2), 535.

Milliken, F. J., & Martins, L. L. (1996). Searching for common threads: Understanding the multiple effects of diversity in organizational groups. *Academy of Management Review*, *21*(2), 402–433.

Mulgan, G. (2017). *Big mind: How collective intelligence can change our world*. Princeton: Princeton University Press.

Nelson, R. R., & Winter, S. (1982). *An evolutionary theory of economic change*. Cambridge, MA: Harvard University Press.

Nonaka, I. (1994). A dynamic theory of organizational knowledge creation. *Organization Science*, *5*(1), 14–37.

Ocasio, W. (1997). Towards an attention-based view of the firm. *Strategic Management Journal*, *18*(S1), 187–206.

Ocasio, W. (2011). Attention to attention. *Organization Science*, 22(5), 1286–1296.

Okhuysen, G. A., & Bechky, B. A. (2009). Coordination in organizations: An integrative perspective. *The Academy of Management Annals*, *3*(1), 463–502.

Page, S. E. (2008). *The difference: How the power of diversity creates better groups, firms, schools, and societies*. Princeton: Princeton University Press.

Pirolli, P., & Russell, D. M. (2011). Introduction to this special issue on sensemaking. *Human-Computer Interaction*, *26*(1–2), 1–8.

Premack, D., & Woodruff, G. (1978). Does the chimpanzee have a theory of mind? *Behavioral and Brain Sciences*, *1*(04), 515–526.

Prendergast, C. (1999). The provision of incentives in firms. *Journal of Economic Literature*, *37*(1), 7–63.

Ridley, M. (2010). *The rational optimist: How prosperity evolves*. New York: Harper Collins.

Roloff, K. S., Woolley, A. W., & Edmondson, A. C. (2011). The contribution of teams to organizational learning. In M. Easterby-Smith & M. Lyles (Eds.) *Handbook of Organizational learning and knowledge management* (2nd ed., pp. 249–271). London: Blackwell.

Sanders, G. S., & Baron, R. S. (1977). Is social comparison irrelevant for producing choice shifts? *Journal of Experimental Social Psychology*, *13*(4), 303–314.

Senge, P. M., & Sterman, J. D. (1992). Systems thinking and organizational learning: Acting locally and thinking globally in the organization of the future. In T. A. Kochan & M. Useem (Eds.) *Transforming organization* (pp. 353–371). New York: Oxford University Press.

Simon, H. A. (1947). *Administrative behavior: A study of decision-making processes in administrative organizations*. Chicago: Macmillan.

Smith, J. B. (1994). *Collective intelligence in computer-based collaboration*. Hillsdale, NJ: Lawrence Erlbaum Associates.

Spearman, C. (1904). General intelligence, objectively determined and measured. *The American Journal of Psychology*, *15*(2), 201.

Stasser, G., & Titus, W. (1985). Pooling of unshared information in group decision making: Biased information sampling during discussion. *Journal of Personality and Social Psychology*, *57*, 67–78.

Steiner, I. D. (1966). Models for inferring relationships between group size and potential group productivity. *Behavioral Science*, *11*(4), 273–283.

Steiner, I. D. (1972). *Group process and productivity*. New York: Academic Press.

Steyvers, M., & Miller, B. (2015). Cognition and collective intelligence. In T. W. Malone & M. S. Bernstein (Eds.), *Handbook of collective intelligence*. Cambridge, MA: MIT Press.

Stroebe, W., Nijstad, B. A., & Rietzschel, E. F. (2010). Beyond productivity loss in brainstorming groups: The evolution of a question. *Advances in Experimental Social Psychology*, *43*, 157–203.

Surowiecki, J. (2004). *The wisdom of crowds: Why the many are smarter than the few and how collective wisdom shapes business, economies, societies and nations*. New York: Anchor Books.

Szuba, T. M. (2001). *Computational collective intelligence*. New York: John Wiley & Sons.

Tapscott, D., & Williams, A. D. (2006). *Wikinomics: How mass collaboration changes everything*. New York: Portfolio/Penguin.

Thompson, J. D. (1967). *The structure of complex organizations*. Harmondsworth: Penguin Books.

Thorndike, E. L. (1898). Animal intelligence: An experimental study of the associative processes in animals. *Psychological Review*, *2*(4), 1–109.

Toma, C., & Butera, F. (2009). Hidden profiles and concealed information: Strategic information sharing and use in group decision making. *Personality and Social Psychology Bulletin*, *35*(6), 793–806.

Ulrich, K. T., & Eppinger, S. D. (2015). *Product design and development*. New York: McGraw-Hill.

Van de Ven, A. H., Delbecq, A. L., & Koenig, R. (1976). Determinants of coordination modes within organizations. *American Sociological Review*, *41*(2), 322–338.

van Knippenberg, D., & Mell, J. N. (2016). Past, present, and potential future of team diversity research: From compositional diversity to emergent diversity. *Organizational Behavior and Human Decision Processes*, *136*, 135–145.

Vosoughi, S., Roy, D., & Aral, S. (2018). The spread of true and false news online. *Science*, *359*(6380), 1146–1151.

Wageman, R., & Baker, G. (1997). Incentives and cooperation: The joint effects of task and reward interdependence on group performance. *Journal of Organizational Behavior*, *18*(2), 139–158.

Watson, A. C., Nixon, C. L., Wilson, A., & Capage, L. (1999). Social interaction skills and theory of mind in young children. *Developmental Psychology*, *35*(2), 386.

Wechsler, D. (1971). Concept of collective intelligence. *American Psychologist*, *26*(10), 904–907.

Wegner, D. M. (1987). Transactive memory: A contemporary analysis of the group mind. In B. Mullen & G. R. Goethals (Eds.), *Theories of group behavior* (pp. 185–208). New York: Springer-Verlag.

Weick, K. E. (1993). The collapse of sensemaking in organizations: The Mann Gulch disaster. *Administrative Science Quarterly*, *38*, 628–652.

Weick, K. E. (1995). *Sensemaking in organizations*. Thousand Oaks, CA: Sage Publications.

Weick, K. E., Sutcliffe, K. M., & Obstfeld, D. (2005). Organizing and the process of sensemaking. *Organization Science*, *16*(4), 409–421.

Weld, D. S., Mausam, Lin, C. H., & Bragg, J. (2015). Artificial intelligence and collective intelligence. In T. W. Malone & M. S. Bernstein (Eds.), *Handbook of collective intelligence* (pp. 89–118). Cambridge, MA: MIT Press.

Williams, W. M., & Sternberg, R. J. (1988). Group intelligence: Why some groups are better than others. *Intelligence*, *12*(4), 351–377.

Williamson, O. E. (1973). Markets and hierarchies. *American Economic Review*, 63, 316–325.

Williamson, O. E. (1981). The economics of organization: The transaction cost approach. *American Journal of Sociology*, *87*(3), 548–577.

Wilson, J. M., Goodman, P. S., & Cronin, M. A. (2007). Group learning. *Academy of Management Review*, *32*(4), 1041–1059.

Woolley, A. W. (2009a). Means versus ends: Implications of outcome and process focus for team adaptation and performance. *Organization Science*, *20*, 500–515.

Woolley, A. W. (2009b). Putting first things first: Outcome and process focus in knowledge work teams. *Journal of Organizational Behavior*, *30*, 427–452.

Woolley, A. W., Chabris, C. F., Pentland, A., Hashmi, N., & Malone, T. W. (2010). Evidence for a collective intelligence factor in the performance of human groups. *Science*, *330* (6004), 686–688.

Woolley, A. W., Gerbasi, M. E., Chabris, C. F., Kosslyn, S. M., & Hackman, J. R. (2008). Bringing in the experts: How team composition and work strategy jointly shape analytic effectiveness. *Small Group Research*, *39*(3), 352–371.

Woolley, A. W., Hackman, J. R., Jerde, T. J., Chabris, C. F., Bennett, S. L., & Kosslyn, S. M. (2007). Using brain-based measures to compose teams: How individual capabilities and team collaboration strategies jointly shape performance. *Social Neuroscience*, *2*, 96–105.

Woolley, A. W., Kim, Y., & Malone, T. W. (2018). Measuring collective intelligence in groups: A reply to Credé and Howardson. Social Science Research Network Paper No. ID 3187373, Rochester, NY. https://papers.ssrn.com/abstract=3187373

Woolley, A. W., Riedl, C., Kim, Y. J., & Malone, T. W. (2017). More evidence for a general collective intelligence factor in human groups: A meta-analysis. Paper presented at the 2017 Collective Intelligence Conference, New York, June 16, 2017.