Intelligent Teamwork: A History, Framework, and Lessons Learned

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Intelligent Teamwork: A History, Framework, and Lessons Learned

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Intelligent teamwork means many things to many people. This paper provides a historical foundation to various elements of human-agent collaboration, leading to the identification of research needs and challenges that are often present when teamwork is seen from the vantage point of cognitive augmentation. A broad research framework consisting of four meshed phases derives from the historical foundation and research needs and challenges to help integrate multifarious considerations involving information, technology, people, and environment is presented. Examples and lessons learned associated with each phase are provided to help articulate requisite bottlenecks and tradeoffs that inevitability arise when agents, aids, and interfaces are purposefully human-centered in their approach. The objectives of understanding, usefulness, usability, and context are examined in consort with each phase.

INTRODUCTION

Cognitive engineering studies often address fields of practice that produce layers of interdependencies that make work challenging, dynamic, complex, and unpredictable at times. Work frequently requires interdependence among individuals –*teamwork*– wherein team plans and actions need to be shared, exchanged, coordinated, interpreted, and adapted to assuage ongoing operations. Teamwork involves team cognition to address problem solving and decision making under conditions of risk. Team cognition is prevalent in a variety of domains in multiple different forms and may exist both internally and externally. While individual and team work rely on internal and external cognition, they also rely on the affordances of the environment (physical, social, and technical surroundings) as specified through information.

Yet, a lot of teamwork is routine and straightforward and can be addressed by prototypical means. Prototypicality represents cognitive processes that are planned, routinized, and anticipated while coordinating responses that consistently address issues, problems or conflicts. In contrast, situations that contain *extreme events* generate non-routine, ill-defined, unexpected, and risk-laden activities that may induce miscalculation, error, and even more catastrophic results (accidents, disasters). These specific situations offer opportunities for problem solving (Hayes-Roth & Hayes-Roth, 1979) and illustrate the demands for *intelligent teamwork.* Intelligent teamwork, in this paper, is defined as teamwork required for a complex situation that is enhanced or augmented through intelligent systems (decision aids, interfaces and tools, and/or human-agent collaboration).

The objective of this paper is to explore how teamwork can be augmented with human-centered intelligent systems: a) when the context contains emergent, complex demands that are unanticipated, and b) to help manage and coordinate interdependencies occurring among information, people, technology, and the environment. A broad research framework of human-agent collaboration (a form of intelligent teamwork) consisting of four meshed phases is articulated.

Historical Precedence in Intelligent Teamwork

Intelligent teamwork can mean many things to many people, but initial work came out of perspectives involving DoD initiatives. A very early example proposed humans talking with intelligent machines (Zachery, Glenn, & Hopson, 1981) to formulate distributed systems. Other early work focused on how cockpit automation technology could impact pilot effectiveness (Kulwicki, 1987). A primary influence on the development of intelligent teamwork came from the USAF Pilot Associate program (Retelle, 1986). Many Pilot Associate explorations focused on the AI/computational needs to allow an associate to aid pilots within a given architectural suite. Adaptive aiding and intent inferencing formed a foundation for coupling pilots with AI. Although the program produced intelligent systems to support the pilot, there was not a strong human-centered emphasis engrained within the design. This was counteracted somewhat with the work of Foushee and Helmreich (1988) who studied group processes and interaction in flight crews, and research focused on electronic crew members. Other work extrapolated the meaning of cognitive science as it related to information architectures, therein taking a much more human-centered approach to AI (e.g., humane intelligence, McNeese (1986); mental models, (Rouse & Morris, 1986). Research during this time frequently focused on workload reduction, situation awareness, and human error, often at the individual level - considering how automation/intelligence would impact human performance. However, one unique perspective sought to understand intelligent teamwork by applying social psychological principles as a basis to intelligent systems design (Wellens, 1993). Yet, most approaches did not necessarily establish the joint interactive effects of intelligent systems and social teamwork. While much has occurred over the last twenty years, there have been very few contributions in establishing contemporary frameworks for developing intelligent teamwork.

RESEARCH NEEDS AND CHALLENGES

When considering intelligent teamwork, four research needs must be explored to engage an interdisciplinary perspective: understanding, usefulness, usability, and context. Woods (1998) suggests an artifact (e.g., human-agent interface) embodies *hypotheses about how the design shapes cognition or collaboration*. The concepts resident in the designs are provided by multiple possibilities in technology. And the hypotheses embody what the designer believes will be useful, which can be subject to empirical testing. This situates research needs through the 'designer as experimenter' role to prescribe human-centric systems.

Human computer interaction approaches to team performance may end up implementing a limited, one-dimensional approach by only addressing usability issues for a single context. This would diminish the ability to address complex systems wherein resilience, sustainability, and adaptive response is necessary for dynamically changing environments. A more informed and broader perspective is to address understanding, usefulness, and usability in succession through developing a top-level view that emphasizes *understanding* the phenomena, theory, and value proponents that underlie the science of teamwork (Woods, 1998).

Understanding is the primary means to discover what intelligent teamwork can provide and through what means it is provided to team members. Usefulness comes from first understanding the phenomena in question prior to addressing usability needs. While usability is important, context demands a broader bandwidth approach. When considering human-agent collaboration as an example of intelligent teamwork, this is even more salient as the findings in this area are limited. Because the framework as elaborated is based on contextual-ecological foundations, it is key that research challenges be commiserate with understanding contextual variation that is apt to occur within intelligent teamwork.

One primary area of concern when working with intelligent teammates (whether human or computational) is (1) being aware of and adapting to the context, and (2) understanding how human-agent interfaces can be useful and usable when work demands context-switching. Context switching occurs in a mission when a team has multiple tasks to address and these tasks switch back and forth temporally producing attention demands to coordinate work across team members. Complex work situations are ripe with changes that create dynamic interdependencies and context switching from one focus point to another. Humans are more adaptive and resilient when they have multiple experiences within a context of work. Yet, they still produce errors and are easily distracted- especially under information overload, stressful conditions, or team shift handoffs. Due to this, cognitive readiness may break down under conditions of uncertainty.

Determining what 'context' means to an interface, aid, tool, or associate is one of the most demanding challenges in intelligent teamwork. Humans have built-in perception and cognitive powers to detect when changes in context occur. In contrast, a computational agent has a limited window of understanding of what context is owing to constrained knowledge representation / information architecture limits. The context has to be programmed into: (1) what the agent knows, (2) what it is doing (planning), (3) where the system is moving to (both conceptually and via navigational landscapes), and (4) how it reacts in extreme conditions. Human-agent collaboration must be systematically addressed in ways considerate of each of these four research needs.

Human Actors Engineering in Intelligent Teamwork

The basis for human-agent collaboration is that it is a set of interactions wherein joint activity is correspondent to accomplishing intentions as the context changes. This has been referred to as "Human Actors" (Bannon, 1991) Actors produce mutual learning to adapt to the demands of the context so work is resilient and accomplishes intentions. This is similar to a growing-living ecosystem. Therein, one of the primitives of the specified approach for intelligent teamwork is that of *human actors engineering.* Human actors must have some type of script that governs their intention while performing capabilities within their means. The script (or model or architecture underling joint activity) is a challenge because augmentation of the human must be anticipated and appropriate to the demands at hand. Knowing what you know about a situation is both contextual and cognitive in that it likely involves function allocation (human or computational control), recognizing whether the intended act is in the repertoire of agent capacitance, and whether the agent has the necessary resources (attention, memory, awareness) to accomplish the task. Furthermore, another unique demand required for complex work is the ability to engage in both deductive and inductive logic when the context switches, uncertainty expands, or information seeking is required. Intelligent teamwork has produced aids or agents with solely rationalistic logic biased towards deductive thought. Alternatively, humans may need more help with cognition that points toward creativity, insights, or imaginative solutions.

Models of AI that typically employ cognitive-information architectures that are computational-driven and reductionalistic may create vacuums when it comes to human-agent interaction. Therein, one requirement is to create an entire new genre of cognitive architectures that produce human-centered design aimed at addressing research needs and challenges. Some of the questions that have arisen through many research studies are:

- How is the architecture for sharing information /making decisions/executing action determined?
- How are activities/functions/tasks allocated at given points in time?
- What determines who is in charge when given the human ultimately is always in charge?
- How does trust emerge among human actors when uncertainty and biases must be addressed?
- Is joint work the subject of social constructivism or some other theoretical perspective?

Given the history of intelligent teamwork and the challenges identified, the paper will now turn towards developing a framework to help facilitate a more systematic approach to the complex issues that emerge.

A BROAD FRAMEWORK FOR HUMAN-AGENT COLLABORATION

Human-agent collaboration is defined and designed for joint intentions that come into play as a mission plays out. The framework first outlines basic questions / concepts necessary to setup what human-agent collaboration is and then what it does. Next, it provides systematic and progressive levels (phases) to look at research trajectories that may necessarily be different but also emerge as knowledge accumulates. To address objectives like this, the framework begins with conceptually-focused questions about what is being considered, as follows: *What level of intelligent support is needed and required to support a human or a team*? It is true that help and support within intelligent teamwork can take the form of a tool, technology, interface, aid, support system, associate, or agent designed for facilitating collaboration within complex environments. Related questions are: *What is the limit of the agent? How does the agent know it is limited in a given situation?*

The approach to the study of intelligent teamwork may evolve through 4 meshed phases. These phases fold into each other to cover the interdisciplinary spectrum of research needs and challenges identified in the previous section. The phases have iterated from a historical examination of a number of cognitive system projects within the government, military, and beyond. Each phase is examined with respect to the degree it implements *understanding, usefulness, usability,* and *context* interests. Before an explanation of the specific details of the phases is provided, the basic level concepts of the framework are explained.

Basic-Level Concepts

The first element of the framework is to describe how intelligent teamwork develops among agents and what the source of their relationships and interdependencies are given the intentions that they hope to accomplish. This concept was first distilled from the theoretical position of A. Rodney Wellens within the C^3 Interactive Task for Identifying Emerging Situations (CITIES) experiments (Wellens, 1993). This framework positions a decision making (or problem solving) entity as interacting with another decision making entity, for a given scenario/problem space where there is *interaction.* The entity comes with a set level of knowledge but has limits in its ability to generate new learning. This can be one kind of limit as certain entities may seek information to acquire new knowledge whereas other entities are more constrained (they can just access knowledge they have or may be even more limited in that they can just perform certain actions when conditions are sensed, such as in an aid). Humans can learn and acquire knowledge in unique ways but agents are not the same. When humans and agents work together the basis upon which they make sense of their world of action must be known and built into the architecture. Intelligent teamwork is conceptualized in the framework to consist of two or more intelligent *agents* (human and computational) in relationship with each other for a given problem where there is a bridge where data, information, signals, and communication are exchanged and transferred. Thus, the bridge is termed the human-agent interface, but is extensible to multiple human and computational agents forming different aspects of teamwork.

Phase 1: Theoretical / Traditional Experiments

Research involving human actors within intelligent teamwork is usually from the tradition of positivist philosophy and engages the theory-hypothesis-test-evaluate cycle that utilizes experimental design / statistical analysis to ascertain whether manipulations of experimental variables significantly influence performance. Phase 1 was very evident of AI in the 1970s to 1980s and is still used by many researchers. Phase 1 historically emphasized the role of *understanding* cognitive processes in intelligent teamwork (human to human interaction). Figure 1 shows the schematic outline of this phase. While much of this phase engages a *positivist stance* in philosophy of science, it is not the only way to understand cognition and determine how human actors explore their environment.

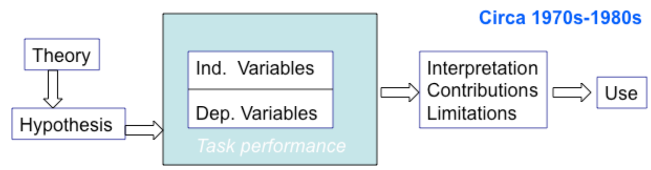

Figure 1. Framework -Phase 1: Theoretical/Traditional Experiments

A historical example of Phase 1 is the work done exploring the role of human actors in intelligent teamwork (both within collocated and distributed environments) (McBride & Brown, 1989). This work utilized the Team Resources Allocation Problem (TRAP) simulation to study replanning and resource management of an emerging set of events. This example produced viable results and demonstrated information-based interdependencies in decision making. They looked at how cognition and perceptual differences in obtaining information could impact knowledge and how knowledge was used as a trajectory into the future- both aspects important for understanding team workload, information sharing, and collective induction, all important areas of intelligent teamwork and potentials for aiding cognition.

One of the early lessons learned was that abstract, intellective tasks (TRAP) required of participants were in line with the goals of experimental psychology but deemphasized the role of practical decision making in the situated context of a mission. Therein, one significant change that occurred was evolving to more real life examples of intelligent teamwork through the use of the CITIES simulation (Wellens, 1993) and the JASPER macrocontext (McNeese, 2000). Both of these represented positivist thinking but CITIES focused more on team situation awareness through more well-defined decision making tasks. Whereas, JASPER represented more ill-defined problem solving where collective induction was important to obtain the best outcomes. The representation of the applied contexts in simulated forms of reality (scaled worlds) was one of the insights developed as it enabled expert knowledge elicitation to inform scenario developments and brought some of the wicked problems in the real world into the laboratory setting.

Phase 2: Traditional Models Emulating Cognition

Phase 2 historically was most active during the 1990s and looked at how theory could inform cognitive models.

Therefore, the objective was to produce models emulative of what a person or team would do. The desire was to produce models that were *useful* so this objective is foremost an outcome. For this phase, development of context representation is low, as focus is typically on 'replacement logic' of an individual, and the use of AI technology is more sophisticated. The phase also speaks to *usability* owing to computational models being compared to humans -then tweaked- to provide human substitutes used in engineering/design assessments. This approach is still very active today, albeit much emulative modeling activity is predicated on human-only performance, and not intelligent teamwork.

Hence one lesson learned is that new advancements need to imbue models to work more interdependently with humans and/or supportive agents for an efficacious orchestration. An early example of emulating cognition was in the provision of an intelligent aid in CITIES. The aid could interact with the user through typical expert system-like, text-based information or as an avatar that emulated interacting with another human expert. This provided an early test of avatars and tested a social psychological theory of interaction, psychological distancing. The initial CITIES simulation was foundational in developing the NeoCities family of simulations that expanded and developed new scenarios, interface modalities, and an advanced information architecture (McNeese et al., 2014).

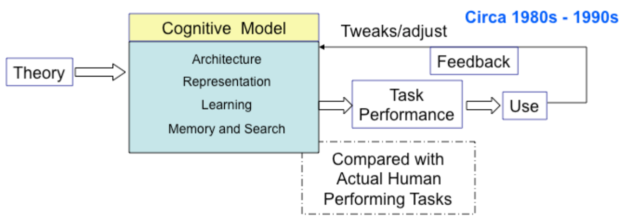

Figure 2. Framework - Phase 2: Traditional Models Emulating Cognition

More contemporary examples of phase 2 might be found in cognitive models of pilots that actually run as parts of a simulation to represent pilot behavior (Jones & Laird, 1997) which can then be compared to actual pilot performance. Another example incorporates affective computing elements and belief states into a cognitive architecture to address a complex AWACS decision making task (Hudlicka & McNeese, 2002). This approach is valuable as it transforms core principles in the cognitive model into specific graphic-user interface effects to aid human actors. This study addressed *understanding* and *usefulness* to directly impact changes in usability that in turn can improve performance.

One of the lessons learned within emulating cognition is that dynamic context needs to be represented in ways that are (1) robust and adaptive and (2) is interpretable as being naturalistic and 'normal'. The CITIES work with avatars was very important in this respect.

Phase 3: Aids/Agents Supporting Cognition

Phase 3 emphasizes the team as being representative of a human supported by agent(s), intelligent interfaces, or aids wherein performance representativeness is determined by comparing human-agent collaboration with an all-human team. Technology use for this phase is generally high but agents or interfaces may not necessarily be human-centered; the role of context is increasing in focus but still a secondary concern. In turn, this phase primarily seeks to advance *understanding* and *usefulness* as objectives in the framework. An example of a different type of aid – the fuzzy cognitive map – helps teams decipher real time updates in the change of the context and supports complex decision making within a distributed decision making task (Perusich & McNeese, 2006). The fuzzy cognitive map equilibrates information from qualitatively different sources and enacts fusion effects via the use of fuzzy set theory.

As mentioned earlier, the NeoCities simulation was designed to advance distributed cognition and test human actors within an emerging crisis management task. One apparent augmentation was the use of fuzzy maps to accumulate information to alert team members to impending conditions (Jones, 2015). Fuzzy cognitive maps are a useful aid as they are dynamic, adaptive, and accumulate uncertainty to threshold levels.

Another example of this phase that is intelligent group interaction (IGI) (Connors, 2006), where an interface can adapt using different principles for distributed teams performing crisis management. This extended NeoCities into the next generation for studying complex intelligent teamwork. NeoCities added new affordances for studying a team of interactive teams wherein adaptive interfaces would tailor integration / information sharing in productive ways. There are many examples of these aids and agents supporting individuals but less so for teams. Therein, this phase is still producing new results that inform intelligent teamwork.

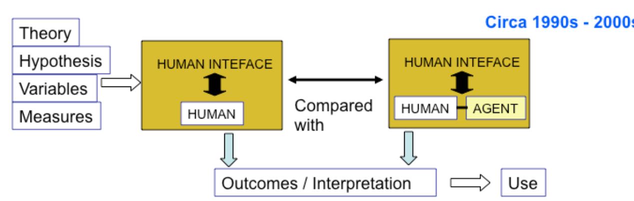

Figure 3. Framework - Phase 3: Aids/Agents Supporting Cognition

One of the primary lessons learned in this phase is the consideration of "when" an agent or aid performs a task is important for acceptance of the agent (trust issue). Also, human-agent task allocation (who does what when for what task) is predicated upon knowing the context more specifically. Breakdowns can occur when an agent has minimal notions of how the context impacts human cognition and planning. Another lesson learned in intelligent interfaces is that human actors are not just invariant, generic entities, but are dynamic and express affective dimensions. Individual differences such as cognitive style play a major role on how they solve problems and make decisions.

Phase 4: Interactive Scaled Worlds

The last phase of the human-agent collaborative framework is highly integrative and blends together various components of agents working with humans in both emulative and supportive roles. The phase is important as it addresses some of the shortcomings mentioned in prior phases, mainly with respect to representing context more robustly and designing teams of agents from a human-centered viewpoint. Because agent teams interact with human teams within a full-capability scaled world, this phase can utilize *usability* as a focus more than other phases, e.g. the use of visualization schemes for members to monitor mutual activity under uncertain conditions.

An example of this phase is research conducted with the Army 3 block challenge problem wherein a team of anti-terrorist analysts switch attention among numerous tasks in the emerging context of their mission (Fan, McNeese, & Yen, 2010). Their focus and attention switching works hand in hand with a team of agents who interpret intentions and actions through a distributed, cognitively inspired architecture termed RCAST. The challenge problem requires noticing perceptual cues in the environment that are shared and processed by an interactive team. The architecture is based on the recognition-primed decision making model (Klein, 1998), and demonstrates the value of designing agent-based architecture from a human-centered design perspective. Therein, phase 4 emphasizes the importance of collective induction (an early aspiration for teamwork mentioned in phase 1), but provides a high degree of coupling of *understanding, usefulness, and usability* with *context.*

Lessons learned are focused upon the priority of providing a scaled world that affords: a) high interdependency and interchangeability among agents, intentions, and tasks as context emerges, b) high complexity that patterns real world perceptual cues in problem solving, and, c) allows joint measurements that reflect information sharing, human-agent trust, and shared contextual awareness as attention switching increases.

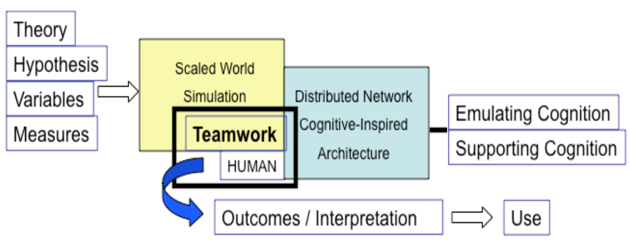

Figure 4. Framework - Phase 4: Interactive Scaled Worlds

FUTURE DIRECTIONS

The research in human-agent collaboration has progressed through four phases over the last forty years to provide a framework that can be profitable for other researchers who wish to conceptualize, apply, and design studies to evaluate and interpret how intelligent teamwork can gain power in complex domains. It is important to know where research has come from (history) as well as where it is leading (trajectories). Our current work is using this framework to expand human-agent collaboration within the context of how distributed teams adapt to emergency medical situations where hospitals and organizations address the spread of diseases, such as, Ebola. The desire is to expand interactive scaled worlds to include the use of the web computing and mobile devices to develop new portals of interaction that include crowd sourcing, citizen science, and the internet of things. This will make distributed cognition more pliable as well as test the limits of how cognitively-inspired architectures can facilitate human-agent collaboration.

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