# Toward a Comprehensive List of Necessary Abilities for Human Intelligence, Part 2: Using Knowledge

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**Abstract.** One of the next steps outlined by [1] in their roadmap toward artificial general intelligence (AGI) is to "refine the list of specific competency areas" in human cognition, providing the keys to human intelligence, ultimately unlocking general intelligence. To that end, here, and in a companion paper [2], I advance toward a more comprehensive list of the necessary abilities for human cognition. The first paper focused roughly on the first half of cognitive processing, from initial input to knowledge construction and memory storage; and this second paper completes the process, with the more action-based second half of using the knowledge for constructive outcomes, and the outcomes as feedback for knowledge updating. It is hoped that the additional refinement will further clarify what we know, and reveal clues for realizing and combining the abilities to move toward AI's grand goal of artificial general intelligence.

**Keywords:** prediction, problem solving, decision making, planning, learning, development, cognition, metacognition, social, language, consciousness.

## 1 Introduction

To reach the high summit of human-level artificial intelligence (or beyond), it makes sense to examine human intelligence itself. In [1], the AGI Roadmap Workshop thus provided a first sketch of the main processes or 'competencies' of human cognition. They also put forth a call to "refine the list of specific competency areas" in human cognition, which this and the companion paper [2] take up. It is indeed hoped that as more refinement occurs others will be inspired to continue the process, and from it draw emergent patterns of how best to realize and combined abilities to accelerate advancement toward human-level AGI. The current paper focuses on the more explicit control processes of the mind/brain: those used to think, act, and learn [3]-[5].

## 2 Necessary abilities for human cognition

As in the companion paper, the tables use simple descriptors for general orientation (I-XII, starting here at VI), with the main abilities numbered 1-29, continuing here at 17. Under each ability I list key specifics, such as critical concepts, types, characteristics, and well-established component processes. Here again overlap exists (such as between problem solving and decision making) and are inevitable since I stand on the side of explicitness, to provide more opportunity to recognize not only weaknesses or omissions, but also apparent patterns when examining a more comprehensive list. Again, only brief additional comments can be made, with the hope that most items are self-evident or can otherwise be found in multiple sources including those cited. We begin with the first step in using the perceived information and relevant knowledge evoked, that of drawing conclusions about it ('VI. Concluding' in **Table 1)**.

**Table 1.** Necessary abilities for human cognition: conclusions drawn and optimal use.

**VI. Concluding**

**17. Judgment: i.e., evaluation of evidence for conclusion (about world state)**

*General processes:*

- Conclusions drawn from Part 1 [2] knowledge construction processes
- Probability estimation; Likelihood
- Other statistical assessments

**18. Prediction**

*General processes:*

- Expectation
- Prediction error

**VII. Using (the knowledge)**

**19. Problem Solving**

*General processes:*

- Search
- Constraint satisfaction
- Sequential, goal-based
- Hierarchical: Subproblems
- Contains or converges to decision making

**20. Decision Making**

*General processes:*

- Valuation
- Choice

*Concepts:*

- Utility Theory
- Heuristics and Biases (key examples below):
  - Loss aversion
  - Alternative hypothesis (and base rate) neglect
  - Availability bias (to overvalue what comes most readily)
  - Attention bias (overvalue that being attended)
  - Hindsight bias (assume 'answers' obvious after knowing them)
- Decisions under uncertainty

- Assessment: to attain the 'best' expected outcome (i.e., objective/goal)
  - Optimization; Risk/Loss/Cost minimization
  - Limited rationality; Satisficing

*Types:*

- Perception-based (overlapping potentially with *Judgment*)
- Goal-based I: Which goal (of potentially multiple)
- Goal-based II: Which action (of action set)
- Goal-based III: Which state (to move to)
- Sequential (e.g., multiple actions necessary to reach goal)
- Partially observable world, states, options (e.g., POMDPs)
- Game theory; Multiagent systems (MAS) (see below)
- Model-free (current-state-based responding); Model-based (choices based on expected outcomes)

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**VIII. Optimizing (over longer-term)**

**21. Planning**

*General types/levels:*

- Tactical
- Strategic
- Automated Planning
- Hierarchical

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**IX. Doing, Taking Action**

**22. Actuation**

*General types:*

- Most general actions: Approach, Acquire/Obtain, Avoid, Escape
- Manipulation: direct; tools
- Navigation
- Communication & Language (see below)

*Considerations:*

- Affordances (interface by which actions influence environment)
- Sequencing
- Coordination (e.g., both legs, hands)
- Based on knowledge at multiple levels (e.g., reflexes to decision-making and metacognition), from multiple competing, interacting systems

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*Judgment* and *decision making* are well-established subfields particularly in behavioral economics and cognitive psychology, with *judgment* formulating conclusions from evidence (usually weak, incomplete, uncertain, probabilistic) [3], [4], [6]. I utilize this operational definition of judgment though it can resolve into other related processes and conceptualizations like conclusions drawn from logical inference, etc. A critical reason for knowledge processing is to anticipate environmental events, i.e., for *prediction*, which has received great attention [7], [8]. Judgment and prediction, though, are only of value when something can be done about it, setting up 'VII. Using'. Often this most directly entails *decision making*, of determining and selecting the best action or course of action (i.e., policy), given the current world state and immediate predictions about it [3], [4], [7]-[9]. Decision making has been actively studied particularly in the human sciences, with well-developed aspects listed. This includes the much-celebrated types of strategies employed, roughly categorized as relying on simpler 'heuristics and biases' versus more deliberative ones [6], [10] [11]-[13]. Key decision scenarios are also included, based on goals, actions, states, sequences (i.e., action policies), in the presence of others (multi-agent, game theory), and in the face of uncertainty and probabilities. Model-free versus model-based decisions capture cases where one simply responds given the current state ('at this stop I always go right') or based on expectations about what the actions bring ('I'm taking right to head home') [7], [8], [14].

And yet, when considered in terms of action sequences, i.e., a policy, decision making and problem solving begin to melt together – and depending on specific implementations they may. Nonetheless, as they remain separable in concept and research work, they remain so here. For example, one may envision problem solving as more overarching, with multiple and different types of decisions made during solving. Moreover, *planning* too can be seen as overlapping with other processes – but nonetheless, entails its own set of issues and characteristics, such as hierarchical planning, and its relation to time horizons and simulation [5]. And although we may not typically consider *actuation* (i.e., action execution) as particularly relevant to intelligence per se, detailed work (especially computationally and neurobiologically) shows how difficult even these problems are, and how they quite likely interrelate with other upstream processes (such as with *affordances*, i.e., the interface by which actions affect the world, e.g., where to grasp objects for effectiveness, and how higher processing may need to take them into account) [15]-[18]. The main types of actions people engage in are listed, along with some key considerations. After action execution, then, there is outcome, which can be used as feedback for subsequent updating and learning; and related to learning is development (**Table 2**).

**Table 2.** Necessary abilities for human cognition: learning and development.

**X. Learning & Development**

**23. Learning**

*General types:*

- Unsupervised (self-organizing) vs. Supervised (binary; answers to train)
- Plasticity (constrained by genes, development, and subsequent structure: e.g., remapping from over or under use, like increase finger representation for violin players)
- Habituation, Sensitization (to single stimuli)
- Associative reinforcement/reward learning:
  - Pavlovian: States/Stimuli (associated with reward)
  - Instrumental/Operant: Actions (associated with reward)

    - Conditioned reinforcement (association chains)
    - Hierarchical: e.g., context learning (occasion setting), actions
- Learning via experimentation (see *Metacognition* below)
- Imitation, Guidance
- With communication & language:
    - Interactive verbal instruction/coaching
    - Learning from written media
    - Teaching

**24. Development**

*General processes:*

- System formation (e.g., neural network formation, culling)
- Prior (genetic) knowledge; instincts, releasing/trigger stimuli
- Critical periods (e.g., sound discriminations for native language)
- Developmental stages
- Language development
- Time/Exposure/Experiential effects (‘trials’)
- Play
- Targeted parental training
- Life cycle influences (e.g., inherent change in preferences)

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*Learning* generally reflects cases using feedback from the environment, although not necessarily for unsupervised. Indeed, it often can be unclear how to distinguish learning from other knowledge creation processes, as the field of machine learning attests. In any case, as with [1], [19], I have listed the most prominent types, with other well-established ones also added, especially from behavioral psychology [7], [20], [21]. Additionally, *plasticity* reflects learning and development interactions [5].

*Development* could obviously be placed under knowledge construction processes, as it is indeed such, but it is placed here as a natural companion to learning (which is also typically a construction process, though normally based on environmental feedback as action outcome). Development is highlighted not only because it builds the necessary apparatus (the brain) in the first place, but because its processes critically influence cognitive processing throughout our lifetimes – even at the highest levels of cognition: e.g., from existing prior knowledge, to change of parameter settings, capabilities, and preferences with life cycle. Moreover, because this is so for humans, it is argued that it requires closer scrutiny for meaning and value for artificial systems: not only for number of training steps required, but also types of experiences, and deeper genetic-environmental interactions underlying all processes [22], [23]. We next examine a critical feature of the human mind/brain architecture that especially comes to the fore from a developmental and evolutionary perspective: levels of processing and control, including metacognition & executive function (**Table 3**).

**Table 3.** Levels of processing and control: including metacognition & executive function.

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**XI. Levels of processing and control: with metacognition & executive function**

**25. Levels with respect to scale**

*Scales involved (for humans, and other primates):*

- Molecules, cells (neurons), networks, systems
- Levels of depth in given circuit (à la deep neural networks: DNNs)
- Levels of neural systems: e.g., brainstem, midbrain, hypothalamus, limbic structures, higher cortical

*Processes:*

- Control general: Modulation and influence
  - Excite, Inhibit, Release
  - Top-down as metacognition and executive function
  - Bottom-up as, e.g., recurrence; ascending pathways (e.g., affect)

**26. Metacognition ('thinking about thinking') and Executive Function**

*Types:*

- Metacognition:
  - If input from lower-level cognitive system
  - All cognitive types: e.g., metaperception, metamemory
- Non-metacognitive: If input higher-level stimuli (e.g., abstract concepts, relations, context), not from lower-level cognitive system

*General processes:*

- Observe, arbitrate, coordinate, optimize, correct, override, control

*Processes:*

- Meta-learning & model ensembles: e.g., voting, averaging, competing
- Monitoring: e.g., task execution, lower systems, outcomes
- Control general: Modulation (excite, inhibit, release)
- Control specific: Attention, Emotion, Self, Learning (e.g., experimentation), Reasoning, Simulation
- Dynamic filtering of memory: Selection & Retrieval
- Manipulation of Working Memory
- Levels of abstraction processing and control
- Flexible manipulation and modifications of knowledge
- (Hierarchical) Planning, Problem Solving
- Figurative description, meaning, metaphor
- Arbitration
- Multitasking
- Awareness/Consciousness
- Self-reflection/assessment/evaluation, correction
- Mind Reading (see under 'Social' below)
- Higher-order emotions: e.g., confidence, self-doubt, dignity

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A fundamental aspect of the human mind/brain is being composed of multiple levels of systems, and at multiple scales. Popular conceptions distinguish basic innate, associative, deliberative, and metacognitive levels, or else more generally as a dual-system structure, though the latter often occurs in the context of human higher cognition, implying a full architecture with additional systems [4]-[6], [8], [14], [16],

[23]-[27]. Although the human mind/brain's exact layered architecture remains unclear, it nevertheless is a critical construction that cannot be ignored; and one where computational modeling will help clarify its structure and value.

For *metacognition* ('thinking about thinking') and *executive function* (whether meta or driven by more sophisticated perceptual input), even though they have been studied for some time, the degree of their influence remains underspecified [5], [6], [16], [27]-[29]. This stems in part from inherent difficulty determining what is meta (or executive) versus basic cognition. For example, in most any implementation of a main cognitive process, such as decision making, it entails some type of higher controlling process over other subprocesses – and thus a form of metacognition (e.g., [8], [30]). Indeed, metacognitive processes can occur for any cognitive system at any level, influencing or potentially controlling those beneath (especially directly below). In any case, the higher levels, and especially the highest most clearly executive, engage in almost any modulatory function one can think of, with substantial evidence for those listed [5], [23], [27], [29]. General control mechanisms are excitatory, inhibitory, or releasing (double inhibitory); with evidence for explicit executive control processes over many of the main cognitive processes, such as attention, emotion, self, etc. Considerations such as these indicate how extensive metacognition is in complex, multilayered systems like the human mind/brain, yet to be fully characterized [9], [17], [18] [29], [31].

Along with what appear to be more general-purpose mechanisms of metacognition and executive function are more specialized ones, significantly organized with respect to the major content domains. And as in [1], [19], here we highlight one of the most important set of content-specialized functions in people: social processing (**Table 4)** [5], [30], [32]-[34].

**Table 4.** Necessary abilities for human cognition: Social knowledge and processing.

**XII. Example content domain knowledge (of particularly importance): Social**

**27. Modeling Self and Other**

*Processes & Characteristics:*

- Self-Awareness: Theory of own mind
- Self-Control
- Theory of (Other's) Mind: e.g., their beliefs, desires, intentions
- Levels of modeling: modeling their models of others' minds, etc.
- Attitudes (beliefs and evaluations of others)
- Attribution (reasons for self and others' actions)
- Empathy, Compassion

**28. Social Interaction**

*Processes & Characteristics:*

- Social perception (e.g., faces)
- Dominance hierarchies, Subordinate strategies, Ownership
- Competition, with strategy (e.g., game theory, multiagent systems)
- Cooperation; Collaboration (with strategy)
- Reciprocity (i.e., reciprocal altruism), contracts, exchange, economies

- Coalitions/alliances, friendship, attraction
- Conformity, role models, leadership, authority
- Hierarchical social organization: e.g., bands, tribes, regions, states
- Appropriate social behavior: convention, norms, rules, laws
- Social morality: e.g., care-harm; fairness-cheating; loyalty; authority
- Social emotions: e.g., pride, embarrassment, compassion, love
- Person, relationship, group knowledge/inference/identity

**29. Communication & Language**

*Processes & Characteristics:*

- Involuntary: normally nonverbal (gestures, facial/body expressions)
- Voluntary: nonverbal, verbal natural language processing (NLP)
  - Comprehension, Production
  - Words/symbols
  - Grammars
  - Recursion
- Pictorial communication
- Language acquisition: listening, speaking, reading
- Cross-modal communication (e.g., sign languages)

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Many research fields – most notably the social sciences, including social psychology and social neuroscience – have recognized the heightened importance of sociality to humans. This has culminated in the extensive evidence for the so-called ‘social brain’: i.e., regions and circuitry dedicated to social processing [5], [33]. It is critical, therefore, to list these as fundamental abilities, as done in the AGI roadmap [1], [19]. I have here extended their list with multiple additional social processes that are especially well-established and actively studied [5], [30], [32]-[34], [47],[48].

At the same time, evidence points to the significance of other specialized content domains – e.g., physical, biological, quantity – as alluded to in other places (especially under ‘8. Knowledge’ in the companion paper), and as indeed recognized in [1], [19]. In any event, the social domain is an excellent representative specialization and of course critical for human and artificial social interaction.

## 3 For artificial general intelligence, are all really necessary?

With the survey completed, we may question whether all listed abilities are relevant for AGI: for example, requiring a developmental critical period or feelings. Given that they all affect the highest reaches of human cognition, it is proposed that some version will be required for full AGI; minimally, all topics should be closely examined, especially for autonomous systems, having more comparable constraints (and problems) as biological organisms. But isn’t it already clear that some forms of human cognition – such as built-in biases (e.g., focused and limited empathy, poor statistical intuitions) or seemingly insatiable low-level drives – are vestiges of ancient evolutionary conditions, detrimental in the modern world? I propose that they retain value however modern the world, with certain conditions (as cognitive illusions) revealing their ‘joints’ (i.e., structure) that must inevitably exist. Exposed failures that yet belie clever solutions underpinning efficiency, resiliency, creativity, still to be fully understood.

Even more enigmatically, it remains vastly unclear the extent true understanding requires the kind of feeling, qualia-experiences, and meta-awareness that humans (and to some degree other animals) have: whether producing our true sense of knowing [5], [35]. It is hard to imagine that consciousness is not fundamental to human intelligence [5], [35], [36]. But short of this, compelling advancement in artificial thinking instills enough inspiration to presume impressive levels of general intelligence will be reached, especially when combining the best approaches, such as symbolic and subsymbolic, notwithstanding current limitations [19], [37], [38].

To address the relevance for artificial systems differently, we might also survey the two papers and conclude that many if not all topics are already being pursued in artificial systems research. Indeed, the topics listed converge well with those of AI and machine learning [25]-[28] [39]. What, then, is missing, as we remain far from human level AGI? A simple answer is that no system to date is fully comprehensive. And even within relatively narrow domains, most remain too brittle, breaking too readily especially in real-world environments. In general, artificial systems need softer landings. Methods for this include probability theory, population coding, broader learning capabilities, movement toward more continuous and dynamic (versus discrete) data, richer data experiences, and levels of processing architectures, with strategies that tune systems at different levels to environmental circumstances, and flexibly label internal representations and recognize their (abstract and relational) similarities [38] [5], [7], [27], [37], [40]-[42].

At the same time, even perception and action are hard problems, limiting for example what inputs higher-level cognitive systems can work with. And even the most basic mechanisms – such as choosing the proper degree of generalization and level of abstraction (to find, e.g., appropriate characterizations of similarity and causality) – prove an art form. This is so even for people, belying a cognitive superpower, that yet oftentimes proves a major source of angst, conflict, and error – underlying many of our well-documented heuristics and biases: leading to oversimplifying, confounding, conflating, attribution errors, stereotyping, profiling, prejudice; or rather, to undergeneralizing, and thus losing advantages of similarity, comparison, analogy, statistics. For artificial systems, although it is right to highlight particularly odd errors – like classifying a pile of towels as a pug dog – it remains unclear how far away they may be: missing deeper meaning or simply requiring more information about the characteristics, contexts, and essence of dogness. There can be a fine line between cleverness, creativity, self-embarrassment versus dysfunction. Either way, for human-*like* ability, the answer lies in the dogness. Beyond shaggy coat and wagging tail, to outer and inner causal features, animacy, personality, and mind [4], [27], [43]-[46].

## 4 Conclusion

Given that the broad strokes of the two companion papers have already been developed in AI and found lacking, answers must lurk in the details – with a critical step being to fill them in, as I have tried to further do. General intelligence also derives from the collective combination of processes, at least among a magical core set properly implemented and integrated – of which a compiled list might help to glean. For this will certainly take a community effort, with collective detailing, developing, edge resolving, and piecing together into an emergent human-level thinking machine.

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