Toward a Comprehensive List of Necessary Abilities for Human Intelligence, Part 1: Constructing Knowledge

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Abstract. In [1], Adams et al. chart a roadmap toward the grand AI vision, with human-level (or greater) intelligence as destination. To that end, in this and a companion paper [2], I take one of the next steps they outline, to "refine the list of specific competency areas" in human cognition. It is argued that we should move toward a comprehensive list of all required abilities to make clearer what is known, unknown, and what the next steps should be, such as resolving how abilities piece together into the larger-scale puzzle of general intelligence. This paper concentrates roughly on the first half of cognitive processing, from initial input to knowledge construction and memory storage (including, for example, emotion, perception, attention, memory, and knowledge construction processes, such as reasoning, imagination, and simulation); with the second paper on the action-based second half that uses the knowledge for constructive outcomes.

Keywords: emotion, perception, attention, memory, generative knowledge, reasoning, imagination, creativity, simulation, artificial intelligence, cognition.

1 Introduction

Even with the ultimate goal of understanding *general intelligence* in its purest form, that is, even beyond what humans achieve and how they achieve it, the human mind/brain cannot be avoided, as it is the best example of – and in fact the only existence proof for – our level of ability. It is undeniably state of the art. Any field interested in intelligence, therefore, should wish to characterize it (a) to obtain insight into how general intelligence can be achieved, whether as a sufficient solution (how can be) or as a necessary one (how must be – at least, potentially, in some aspects); and, minimally, (b) to compare alternative developments to it, to assess their distance. Thus, it makes sense to have detailed, comprehensive information about human general intelligence as a roadmap toward artificial general intelligence (AGI) [1], [3].

Following the AGI *narrow* versus *general* distinction, with narrow enabling domain-specific capacity, general ability in psychology is typically captured in the concepts of *intelligence* overall or in *higher-level* cognition. But regardless, even highest-level cognition requires and builds from basic cognitive abilities that span from perception to action (especially given the tight coupling of processes and systems throughout the human mind/brain). Therefore, as realized in [1], [3], the AGI path forward requires consideration of the entire core set of abilities for human cognition in general (with an eye toward its necessity for higher cognition and general intelligence). To this end, then, the AGI Roadmap Workshop provided an initial list of human cognitive abilities or ‘competencies’ [1], [3]. Although the list provided is excellent, which I build from here, as they said, it was nonetheless considered intuitive and necessarily lacking, given their sense that a complete list may be “beyond the scope of current science”.

Contrary to this view, however, I believe there is enough evidence from psychology, neuroscience, and related fields (e.g., AI, machine learning) to attempt to move toward a comprehensive list. And even as [3] rightly points out that different people may all generate different lists, I yet believe it serves the community best to share such attempts at comprehensive lists, to provide a richer set of possibilities for AGI researchers to consider, as well as help lead to a convergent one [4]. Moreover, once listed explicitly, it becomes easier to identify larger patterns or expose omissions, leading either way to more efficient advancement. In fact, included in [1]’s list of next steps is to “refine the list of specific competency areas”, which I attempt here.

I do so in a set of eight tables: four in the current paper, from initial input and system activation to knowledge construction; and then in the companion paper [2], four more, covering knowledge using. The papers may also be seen as roughly divided with respect to human neocortex: i.e., sensory-perceptual processing to knowledge construction and maintenance in posterior cortex, and more active thinking and action regions of frontal cortex (with areas like posterior parietal cortex transitional).

Together, the eight tables form a comprehensive list of human cognitive abilities (or competencies), and thereby general intelligence. It results from numerous references that cannot all be cited, with special emphasis on collating the most well-established processes from leading textbooks in the relevant fields: especially psychology (multiple subfields), cognitive neuroscience, AI, and machine learning (e.g., [5]-[13]).

Finally, we might ask whether such a compendium already exists. Textbooks in particular generally do this, yet they typically take some specialized perspective, remaining therefore incomplete. As well, psychology and neuroscience have generally been loath to consider a comprehensive, more global perspective (as being potentially too daunting and premature), leaving the task to those requiring it, such as metacognitive researchers (who must ask, e.g., what systems in the brain are being monitored and controlled), roboticists, and those ambitious enough to accept the grand AI (now AGI) challenge.

2 Necessary abilities for human cognition

The topics across the two papers are organized following a rough input-to-output structure, with higher level descriptors for general orientation (I-XII), and numbering of main abilities (1-29). Under each ability I list key specifics, such as types, component processes, and other characteristics. Obvious and apparent cases of overlap indeed exist and are inevitable since I err on the side of explicitness, especially in cases where researchers have carved out an active niche, including the study of comparable topics under different more general ones (e.g., generalization and discrimination, required most everywhere). Listed together they should help clarify where further work is especially needed, to help establish the most fundamental abilities, better resolve their edges, and determine how best to assemble them. Finally, only brief comments can be made, with the hope that most items in the tables are self-evident enough, and/or can otherwise be readily found in multiple sources like the ones cited. We begin then with perhaps a first set of counterintuitive necessary processes, listed in **Table 1**.

Table 1. Necessary abilities for human cognition: the need to care.

I. Caring

1. Arousal & State (internal)

Processes, State (internal):

- Arousal as activating system:
  - Wakefulness
  - Alertness, Readiness
  - Nervous system energy level, power
- State: Sense of physiological condition, from all arousal processes

2. Sensation

Types:

- Pain
- Touch
- Proprioception, kinesthesis, body state

3. Motivation: Drive, Desire

Types:

- Affect-based motivation 1.0 (needs, drives):
  - Intake: fluids, food
  - Other homeostasis: temperature control, health
  - Avoiding threats, germs
  - Mating and sexual: attraction, competition
  - Parenting and family
  - Social: cooperative, competitive
  - Sleep
  - Life-cycle based
- Affect-based motivation 2.0: desires: wanting, liking/disliking

Triggers/Signals/Input stimuli:

- Internal: homeostasis signals (e.g., hunger)
- External:
  - Instinctive value (+/-) of state/stimuli
  - Pavlovian value (+/-) of state/stimuli associated with reward

Processes:

- Pavlovian conditioning: state/stimuli associated with reward
- Operant/Instrumental conditioning: action associated with reward
- Related: Self-Control of lower-drives, desires, temptations (next)

4. Emotion, Mood, Feelings, Feeling

Types & Processes:

- Emotion: Produces shorter-term feeling (with lower physiological response) to stimulus
  - Basic: surprise, fear, anger, happiness, sadness, disgust
- More complex: e.g., pride, embarrassment
- Mood: middle-term feeling, higher-level general (internal) state
- Feelings: longer-term feeling (with lower physiological response) toward stimulus (e.g., "I love her/him.")
- Feeling (and sensations): higher-order sense, appraisal of 1-4 (e.g., "How are you feeling?")
- Communication:
  - Nonverbal expressions
  - Perceiving/interpreting
- Emotion control (see below)

This first table may appear an odd start, but it is becoming clearer how fundamentally integrated the human mind/brain is and how even the highest levels of cognitive processing are affected by the lowest (e.g., arousal functions) [14]-[21] – quite simply, we need to care, and we seem to need to *feel it*, to truly understand something, discussed more below [10], [22]. We should note that predominantly, though not always, neurochemistry (as neurotransmitters, neuromodulators, or hormones: e.g., acetylcholine, dopamine, endorphins, androgens) plays a fundamental role (in items 1-4) [18]. For arousal, more than just trivially (e.g., must turn on power to use), its subfunctions infuse neural systems with ease of processing and effort, influencing capacity, processing speed, thinking deliberativeness, motivation, valuation, etc. Consider, for example, how caffeine influences thinking ability (blocking adenosine receptors, thereby enhancing dopamine's arousal and concentration effects) [23]. For '*4. EMFF'*, specific definitions change with author, but all concepts are fundamental and require some operational definition, with these common [10], [22]. Together they arise from an intricately coupled set of stacked systems, gradient like, distinguished significantly by the brain subregions (e.g., brainstem, midbrain, hypothalamus, limbic, and higher cortical regions) and neurochemistry, arising from typically lower regions (e.g., midbrain, hypothalamus & pituitary) and infused into mid and higher ones (especially limbic regions, such as the ventral striatum of basal ganglia and deeper prefrontal areas) or as hormones directly into the bloodstream [10], [18]. These details provide a sense of the rich relationships of lowest to highest level processes, becoming more appreciated, though not fully yet. Only then, when the system has cause to, once it cares, it perceives and attends (**Table 2**).

Table 2. Necessary abilities for human cognition: perceiving and attending.

II. Perceiving

5. Perception: Low (Sensory) to High (Recognition/Identification)

Modalities:

- External stimuli/input: Vision, Audition (Hearing), Smell (Odor), Somatosensory (Touch), Taste, Cross-modal
- Internal stimuli/input: Proprioception, Kinesthesis; Homeostasis/drive-based: hunger, thirst, temperature, sexual, parenting, social

General Processes & Characteristics:

- Filtering, amplifying, search, selecting, constructing
- Dimensionality reduction; transformations; convolution
- Classification (e.g., template matching)
- Clustering (more unsupervised)
- Discrimination & Generalization
- Moving toward categories, concepts, relations, systems of relations.

III. Attending

6. Attention

Systems:

- Stimulus-driven (bottom-up or exogenous)
- Goal-directed (top-down or endogenous)

General Processes:

- Selecting, filtering, amplifying, search

Perception is often divided into early, middle, and late processes or stages, and in any case, from low to high, with the latter seamlessly transitioning to more centralized cognitive or thinking processes. Indeed, perception itself involves integrated attentional and more centralized processes (such as memory access), with machine learning, neural-network modeling, and cognitive neuroscience helping to better appreciate this and flesh-out details (e.g., [10]). For internal modalities, body signals lead to perception of state, sensations, emotion, feeling (thus overlapping with caring processes). For attention, two general systems are recognized as listed [10], [24]-[26]. From perception and attention, then, we come to knowing: memory and knowledge (**Table 3**).

Table 3. Necessary abilities for human cognition: memory and knowledge.

IV. Knowing

7. Memory

Types:

- Implicit (long-term, unconscious)
- Procedural (a form of implicit that underlies habits, routines)
- Episodic (event-based)
- Semantic (explicit knowledge/fact-based)
- Short-term (as buffer, with no obvious manipulation)
- Working (short-term, with manipulation, conscious awareness)

General Processes:

- Encoding
- Retrieval
- Restructuring
- Forgetting
- Suppressing, repressing

8. Stored Knowledge (contents of memory)

Representation/organization/ontologies:

- General 1: templates; exemplar matching; levels of abstraction
- General 2: organization: graphs (e.g., tree: hierarchical; chains)
- General 3: features, objects, categories, concepts, relations, abstract relations; causal chains; systems of relations/chains; context; person; problems; events; event complexes; scripts
- Uncertain knowledge
- Values and beliefs
- ***Content Domains***:
  - Physical:
    - physics (natural objects, movement)
    - space, time; object properties, dynamics, interactions
  - Biological (organismic) & (bio)chemical (cellular, molecular):
    - flora, fauna: as resources, threats (including germs, sickness, medicinal)
  - Social:
    - Individual & Group: cooperative, competitive/threats
    - More detail in [2]
  - Technical: Artifacts
  - Quantitative, relations, statistical

Management/manipulation/execution processes:

- Search, select, sort and 'data' organization
- Chunking, symbolic labeling & processing, cross-referencing
- See under perception, memory, metacognition

For memory, I have listed the well-established types as in [1], [3], as well as main general processes [5], [10], [27]; then for stored knowledge, detailed descriptions of its key concepts, characteristics, and processes. Under *General 1* are popular general models in psychology, most clearly for categories, but also beyond this [5], [6], [10], [28], [29]; *General 2* lists basic organizational structures [6], [30]; and *General 3* the main types of content elements actively recognized and studied [6], [31]-[33]. *Content domains* have received considerable attention in multiple fields, including comparative and developmental psychology, with substantial evidence for them as actual organizing ontologies for knowledge and memory – even potentially as innate priors [7], [21], [34]-[37]. *Management processes* are a representative list of necessary and important data management processes in the human mind/brain (also being a good example of the current and perhaps necessary overlap with other main processes listed in the tables). **Table 4**, then, addresses how this knowledge is constructed.

Table 4. Necessary abilities for human cognition: knowledge construction.

V. Knowledge Construction

9. Generalization & Discrimination

Characteristics & Processes:

- Recognizing/Isolating invariant structure
- Similarity matching (e.g., feature distance)
- Discrimination/Dissimilarity
- Regularization (i.e., methods to minimize overfitting)

10. Abstraction, Elaboration, Reduction

Processes:

- Recognizing/Building hierarchical relationships of entities and their features – and moving up and down these hierarchies
- Segmenting entities into subcomponents (e.g., parts, substance)
- Inferring/Creating unseen factors and relationships (e.g., cells, forces)
- Concept formation

11. Symbolic processing

Processes:

- Labeling denotive items
  - Externally: labeling/naming
  - Internally: internal representation label (e.g., vector quantization)
- Recognizing/Using symbols
- Verbal invention

12. Reasoning

General processes:

- Basic Logic
- Sequence modeling
- Inference
- Explanation; Argument
- Rule formation
- Using other rules, methods of thought (e.g., visuospatial)

Types:

- Associational (i.e., general relationships)
- Deductive (i.e., effects from causes)
- Inductive (general rule, principle, pattern from observations)
- Abductive (i.e., causes from effects)
- Causal (i.e., cause and effect identification and relationships)
- Analogical (similarity, esp. of relationships, across content domains)
- Deontic (i.e., rules, obligations)

- Fictive ('what if?')
- Probabilistic
- In specific content domains: e.g., physical, social, quantitative

13. Modeling: Identifying patterns, structure

General processes:

- System identification/State estimation
- Structure learning (like of graphs or trees)
- Latent variable models
- Feature discovery
- Function approximation/identification (e.g., regression)

14. Generative construction (and deconstruction) and execution/control

General processes:

- Used throughout cognitive abilities list
- Sequences; hierarchy (i.e., all graph structures)
- Recursion
- Restructuring for consistency
- Formulating beliefs
- Specific content domains:
  - Physical: tool use, manufacture (from tools to technology)
  - Psychological & Social: Modeling self and others' minds
  - Other social construction: e.g., group structures, communities; language (and grammar)

15. Imagination, Creative thinking

General processes:

- Figurative: creative tropes: e.g., metaphor, associations (fiction, humor)
- Originality: combinations; novel conceptions, creations (some art)
- Examples: Philosophy, Mathematics, time travel, discovery

16. Simulation

General processes:

- Forward, backward in time
- Visual imagery, transformations (e.g., rotation)
- Internal theater as mind's eye (or ear, etc.)
- With other processes, such as working memory, fictive reasoning

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Knowledge creation includes main processes actively studied both with respect to mind and brain, but also in machine learning (where work highlights the significance of the specific processes, and provides more critical details) [5]-[7], [11]-[13]. *Generalization* and *discrimination* are separated from *abstraction* and *reduction*, with the former two as potentially more lower-level and generic, and the latter two focused more on hierarchical relationships and levels of analysis [6], [21], [38]. *Symbolic processing* is widely recognized as a hallmark of human cognition – as we continue to appreciate its power beyond specific domains such as language. Of course, symbolic-level models have appreciated it; but as subsymbolic approaches accelerate, their interface to the symbolic becomes even more critical (with layered architectures and techniques such as vector quantization – essentially labeling vectors – promising approaches [13], [39]). *Reasoning* highly depends on one's operational definition of it, since if broad enough, could subsume most all the more central information processes. However, in psychology, for instance, it has come to represent more obvious cases of (typically) sequential logical construction and inference (e.g., transitivity: if A=B, B=C, A=?). Even then, there are many types of reasoning, as shown [6]. *Modeling* is listed separately, with 'mental models' a defined area of psychological research, as well as more directly contacting related work such as in machine learning (e.g., system identification) and social processing (e.g., mind reading) [6], [9], [12], [13].

Although potentially overlapping with others, and in any case necessary for many, as in [1], [2], *generative construction* is emphasized to catalog the mechanisms for active knowledge creation – with the most quintessentially human being *recursion* [1], [3], [6], [12], [13], [38], [40]. *Imagination* and *creative thinking* are also listed, with active research areas such as *creative cognition*, and the greater appreciation of being fundamentally critical for such things as building problem representations in the first place, and not only discovering but creating novel problem solutions [5], [14], [15], [31] [32], [41]. And *simulation* is highlighted as a fundamental means by which humans think about, plan, and imagine the world [6], [10].

Finally, knowledge construction is a dynamic and highly interactive set of processes also influenced by the act of using the knowledge – processes taken up in Part 2 [2].

3 Are all necessary for intelligence & more than obviously so?

For humans the answer appears a resounding, 'yes'. Not that all are necessary in all or most cases; but it is proposed that in some form, full human capability requires them, with broader and tighter integration than typically expected. For example, 'why' and 'how' human cognition is carried out is continuously influenced by the "I. Care" processes: e.g., mood and arousal state influencing which level and type of processing conducted, such as heuristic versus more deliberative reasoning and problem-solving processes [10], [14], [22], [29]. One way to imagine this are days (such as weekends) when one's own work looks 'Greek' and difficult to decipher; when a regular trip (such as to office) feels particularly far or near; the ambition of mornings versus late evenings; or after a strong cup of coffee. Moreover, perception requires memory and knowledge interpretation, in turn influenced by the problems to solve, actions to take, and so on; thus, naturally spanning all main components of intelligence. One may, nonetheless, question the necessity of some for artificial systems – e.g., why do they need to care if their algorithms reflect our interests? [2] returns to this once the entire list is complete.

4 Conclusion

The current set of cognitive abilities – caring, perceiving, attending, knowledge, and knowledge creation – already shines light on remarkable abilities of humans, including and perhaps especially to recognize and identify where meaning actually lies: beneath the apparent, perceptual surface. And not only to envision this otherwise hidden world in the mind's eye, but, together with the abilities in *Part 2*, create our own versions in the shared, external world – thereby testing out and ultimately thriving by our knowledge, inferences, flights of imagination.

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