

# Technologies Smarter, Humans “Dumber”?

## How Technology Improves and Diminishes Human Cognition and What This Means for Education

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**Disclaimer:** Obviously, tools such as ChatGPT 5.2, Elicit, Grammarly, and others have been used in assisting with the analytical groundwork and drafting of this paper. **In line with the arguments made in the paper, the cognitive effort involved in developing the arguments and controlling the paper's logic has not been outsourced; those operations remain the sole responsibility of the human authors.**

# Abstract

Technological innovations have repeatedly transformed human cognition by externalizing, amplifying, and reorganizing knowledge and skills. While the economic and institutional consequences of technological change have been extensively studied, its long-term cognitive and epistemic effects remain underexamined. This paper conceptualizes technology as an epistemic change agent. It examines how successive technological innovations—from writing and printing to digital media, smartphones, and artificial intelligence—have altered human cognitive capabilities and the conditions for learning. Drawing on twenty historical case studies, the paper identifies recurring patterns in the educational consequences of technological change, including cognitive offloading, attentional fragmentation, and the displacement and transformation of tacit knowledge, rising epistemic opacity, and shifting forms of authority and expertise. **The analysis shows that technological progress consistently produces both cognitive gains and losses: while technologies expand abstraction, efficiency, and access to knowledge, they simultaneously weaken embodied, contextual, and internally sustained capacities that education has traditionally cultivated.** *To address this tension, the paper proposes a five-layer framework of cognitive competence—foundational capacities, procedural skills, conceptual understanding, integrative sense-making, and epistemic meta-competence—and analyzes how each layer is differentially affected by technological delegation. The paper argues that the central educational challenge is not whether to adopt new technologies, but how to rebalance learning to preserve attention, understanding, judgment, and autonomy in increasingly automated knowledge environments.* **The conclusion outlines implications for curriculum design, pedagogy, and education policy in the age of artificial intelligence, across five layers:**

5. **Epistemic meta-competence: judgement/discernment, adaptability.**
4. **Integrative sense-making: breadth; far transfer.**
3. **Conceptual understanding: depth at discipline- and subject-levels; near transfer.**
2. **Procedural and declarative: partial, curated depth.**
1. **Foundational abilities: attention, memory, etc.**

## Introduction

In this paper, we examine the impact of technological innovation and change on human cognitive capabilities. The paper is structured as follows. First, we discuss the theoretical foundations of the claim that technology functions as an agent of epistemic change. In that section, we also situate our approach within current thinking on how

technology fuels economic growth and social progress. Next, we present a historical analysis of how technological breakthroughs have altered human knowledge, skills, character, and meta-learning (hereinafter referred to as competencies). The groundwork for this analysis was prepared through twenty case studies of past and recent technological innovations, which are presented in the Annex. Based on these case studies, we discuss the patterns that emerge from the historical analysis. We then delve more deeply into several specific topics, including cognitive offloading and attentional fragmentation. Finally, the concluding section addresses how to balance the cognitive enhancements of technological innovation with the cognitive impairments it entails, and the implications of this analysis for education.

An analysis of human cognitive losses always has the risk of hodiecentrism<sup>1</sup> or the tendency to romanticize the past.<sup>2</sup> We must never forget the benefits and enhancements that technological advancements bring to humanity. Enhancements and diminishments are not to be seen as opposite sides of the coin, but are often intrinsically linked. What brings progress also entails loss. Our analysis is not about techno-optimism or techno-pessimism. However, a deeper understanding of the cognitive ramifications of technological innovations is necessary to design effective epistemic and educational strategies that fully enhance human potential.

## Technology as an epistemic change agent

Technological innovations are agents of change in knowledge and competencies. They can be seen as epistemic change agents, reconfiguring the production, validation, transmission, and use of knowledge. They render some knowledge and competencies obsolete, creating new ones. This is the paradox of innovation: technological advancements enhance specific human capabilities, yet they also erode others. Cognitive erosion is an underexplored side effect of technological innovation.

In recent years, historians and economists have studied the history of technological innovation in relation to economic growth, social progress, globalization, inequality, and, at times, to the history of education. For example, Claudia Goldin & Lawrence Katz analyzed the impact of technological innovation on the demand for abstract and analytical skills.<sup>3</sup> When education systems adapt, technological change can lead to prosperity; if not, the consequences include inequality, deskilling, and polarization. Joel

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<sup>1</sup> Hodiecentrism is the tendency to interpret the past through today's lens.

<sup>2</sup> Hong, Z. (2025). An Imagined Golden Past: The Cognitive Foundations of Decline Narratives in Human Societies. [https://doi.org/10.31234/osf.io/kfd3g\\_v2](https://doi.org/10.31234/osf.io/kfd3g_v2)

<sup>3</sup> Goldin, C., & Katz, L. (2008). *The Race Between Education and Technology*. Harvard University Press.

Mokyr assessed the contribution of knowledge and a culture of inquiry, dissent, and circulation of ideas to technological advancement and economic growth.<sup>4</sup> Knowledge systems contributed to growth if they enabled a shift toward experimentation, explanation, persuasion, and cross-domain reasoning. Oded Galor developed the “unified growth theory,” in which growth emerges from feedback loops among technology, population, human capital, and institutions.<sup>5</sup> Technology stimulates the expansion of abstract, transferable knowledge and leads to the decline of subsistence know-how. Daron Acemoglu & Simon Johnson analyzed the contribution of technology to growth and progress by looking at the institutional governance of technological change.<sup>6</sup> The outcomes of technological change depend on power structures and institutional design. Inclusive design leads to broad prosperity, but otherwise, the concentration of epistemic and economic power results in polarization between elite expertise and deskilled labor. Most recently, Carl Benedikt Frey argued that, for much of human history, stagnation was the norm and that, even today, despite significant technological advances (e.g., AI), gains may flatten if institutions don’t adapt.<sup>7</sup> It’s not enough to invent or adopt technologies; the institutional ecosystem must fit the technologies and evolve. The tension between decentralized innovation (“exploration”) and centralized scaling (“exploitation”) is a recurring institutional dynamic. He argues that societies need both decentralized networks to generate new ideas and centralized/bureaucratic structures to scale them; however, if one dominates or becomes rigid, stagnation ensues.

These authors converge on the insight that technological progress is neither automatic nor epistemically neutral. They have contributed to the understanding that knowledge systems are critical for economic growth and social progress by focusing on the institutional embedding of knowledge (Frey), the importance of social and cultural norms (Mokyr), the governance of innovation (Acemoglu & Johnson), or the human capital thresholds of economic growth (Galor). However, they do not address the impact of technological change on human cognition.

Technological innovations impact human cognition. They alter our mental energy, memory, and attention. For example, they cause individuals to offload or outsource cognitive operations (e.g., spatial memory in the case of GPS). Cognitive offloading

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<sup>4</sup> Mokyr, J. (2016). *A Culture of Growth. The Origins of the Modern Economy*. Princeton University Press.

<sup>5</sup> Galor, O. (2022), *The Journey of Humanity. The Origins of Wealth and Inequality*. Penguin Publishing Group.

<sup>6</sup> Acemoglu, D. & Johnson, S. (2023). *Power and Progress: Our Thousand-Year Struggle Over Technology and Prosperity*. Public Affairs.

<sup>7</sup> Frey, C.B. (2025). *How Progress Ends: Technology, Innovation, and the Fate of Nations*. Princeton University Press.

shifts our mental operations from internal knowledge to external memory. This means a change from knowing to knowing where to look. At a higher level, technological innovations displace knowledge systems (e.g., orality, artisanal crafts). At a societal level, they alter power relations and social hierarchies (e.g., the printing press privileged literate elites). They also redefine epistemic legitimacy, i.e., who counts as knowledgeable, as evidenced by the marginalization of indigenous systems. As a consequence, technological innovations redefine who can be trusted. They lead to the emergence of specific professions that embody new knowledge and diminish the epistemic authority of traditional knowledge carriers (e.g., folk medicine versus medically trained doctors).

In this paper, we will explore these changes. The groundwork of our historical analysis is provided by twenty case studies of technological innovation and their epistemic consequences. These case studies can be found in the Annex.

# The epistemological history of technology

## Historical synthesis

The case studies in the Annex reveal a recurring cycle: **each technology—from fire to AI—expands human knowledge in scale, precision, and durability, while simultaneously eroding older knowledge and competencies, narrowing specific perspectives, and redistributing authority.** Technologies constantly restructure what counts as knowledge, who controls it, how humans relate to it, and how societies remember or forget.

Across historical phases, technology functions as an epistemic scaffold: from prehistoric tools that stabilize embodied survival knowledge, to classical techniques that externalize memory and spatial reasoning through writing and construction, and onward to early modern systems that standardize time, representation, and reproducibility. The industrial phase deepens this shift by abstracting and automating labor, producing increasingly specialized forms of technical knowledge. In contrast, *the digital phase marks a qualitative transition in which cognition itself is partially delegated to algorithmic systems.* Read longitudinally, Table 1 suggests that technological change is less about isolated inventions than about cumulative transformations in how knowledge is encoded, validated, and operationalized—*moving from tacit, context-bound understanding toward formalized, computational, and symbolic regimes that increasingly overhaul human epistemic agency.*

Historical Phase	Core Transformation	Epistemic Shift	Illustrative Technologies
<b>Prehistoric</b>	From survival know-how to managed environments	Embodied → Proto-symbolic	Fire, Agriculture
<b>Classical</b>	Externalization of memory and spatial logic	Oral-tacit → Textual and quantified	Writing, Construction
<b>Early Modern</b>	Temporal and representational standardization	Contextual → Measurable and reproducible	Timekeeping, Printing
<b>Industrial</b>	Automation and abstraction of labor	Manual → Technical-specialized	Mechanization, Chemistry, Electricity, Refrigeration
<b>Digital</b>	Delegation of cognition to algorithms	Cognitive → Computational	Computers, Smartphones, Internet, AI
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**Table 1. The evolutionary trajectory of the epistemic consequences of technological innovation**

## Patterns

Throughout the historical analysis of technological innovations, as described in the case studies, some patterns emerge:

- Expanding and replacing knowledge and competencies: Across virtually all cases, technological innovation expands the scope of what humans can know and do, while simultaneously narrowing or displacing older competencies. New technologies amplify specific cognitive capacities (prediction, abstraction, precision, scale). At the same time, they erode embodied, situational, or tacit knowledge and skills that are no longer required.
- The progressive externalization of cognitive functions: from memory and calculation to perception, navigation, judgment, and now explanation. Knowing increasingly means knowing how to work with systems that know. This pattern is summarized in Table 2.
  - Material externalization: fire, tools, infrastructure
  - Symbolic externalization: writing, numeracy, diagrams

- Mechanical externalization: clocks, printing, machines
- Digital externalization: calculators, computers, GPS
- Generative externalization: AI systems that produce knowledge-like outputs

Phase of externalization	Core technologies	What is externalised	Epistemic shift
<b>Material externalization</b>	Fire, tools, shelters, infrastructure	Physical effort, perception–action coupling	Human cognition is extended through environmental manipulation
<b>Symbolic externalization</b>	Writing, numeracy, diagrams	Memory, representation, abstraction	Knowledge becomes portable, cumulative, and transmissible
<b>Mechanical externalization</b>	Clocks, printing press, machines	Timing, repetition, standardised execution	Knowledge and work become regularised and scalable
<b>Digital externalization</b>	Calculators, computers, GPS, search	Calculation, retrieval, navigation	Cognition becomes fast, searchable, and externally reliable
<b>Generative externalization</b>	AI systems producing text, images, code	Drafting, synthesis, explanation, pattern generation	Knowledge production becomes delegable and opaque
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**Table 2. Phases of Cognitive Externalization**

- *move from local, context-bound knowing toward standardized, transferable representations:* Knowledge becomes measurable (time, space, energy, purity), codified (texts, protocols, algorithms), portable and interoperable across regions and institutions.
- *Redefining epistemic legitimacy:* Technological innovations redefine epistemic authority in establishing what counts as evidence, truth, or competence. Authority moves from who knows to what system produces an answer.
  - Writing privileges documents over memory
  - Print privileges stable texts over oral debate
  - Instruments privilege readings over senses
  - Media privilege images over testimony
  - Algorithms privilege statistical regularity over explanation

- *The oscillation between deskilling and reskilling:* The case studies show that deskilling is never total; it is domain-specific and paired with reskilling. **The long-term pattern is that low-level, routineized skills decline, while higher-level coordination, abstraction, or judgment skills increase.**
- *The decline of epistemic transparency and the increase in opacity and dependency:* **Knowledge becomes powerful but less inspectable by ordinary knowers.** Whereas in earlier technological innovations, users could still see the causal chains, in more recent technological transitions, knowledge systems operate behind interfaces and algorithms. The result is increased vulnerability to failure, manipulation, and misinformation, the rise of expert systems and institutional dependence, and the emergence of new inequalities between those who can interrogate systems and those who cannot.
- *The compression of epistemic distances, and the time and space of learning:* Technological innovation repeatedly compresses the distance between question and answer, between event and representation, between novice and expert performance.
  - Print accelerates scholarly exchange
  - Media collapses witnessing distance
  - Computers collapse calculating cycles
  - Smartphones collapse learning into micro-moments
  - AI collapses explanation, drafting, and translation into seconds

Table 3 summarizes the key historical patterns across our twenty case studies of the epistemic impact of technological innovations, including the benefits and losses.

Pattern	Core dynamic	Typical benefits	Typical losses
<b>Expansion &amp; narrowing</b>	Some capacities expand as others shrink	Precision, speed, abstraction	Loss of embodied or tacit skills
<b>Externalization of cognition</b>	Cognitive work shifts to tools	Scalability, efficiency	Dependency, skill atrophy
<b>Situated to standardized knowledge</b>	Local know-how becomes codified	Interoperability, coordination	Loss of context and plurality
<b>Redefinition of authority</b>	Systems replace experience	Objectivity, comparability	Opacity, power concentration
<b>Selective deskilling</b>	Routine skills replaced	New higher-order roles	Unequal transitions
<b>Epistemic opacity</b>	Systems become black boxes	Powerful tools for non-experts	Fragility, over-trust
<b>Compression of time &amp; learning</b>	Distance between question & answer collapses	Speed, access	Shallow understanding
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Table 3. Key historical patterns in the epistemic impact of technologies

## Changes in human cognition

What do these patterns imply for human knowledge and competencies? Each case study demonstrates significant changes in what humans can know and do. Taken together, the most important changes are:

- *Externalization of memory*: Each technology shifts tasks from human memory or perception to external artifacts – from fire (outsourcing warmth and light) to writing (outsourcing memory), to digital tools (outsourcing reasoning and recall).

- *From tacit to explicit knowledge*: Repeated transitions show tacit, experience-based skills being formalized and codified — e.g., oral traditions replaced by written records, artisanal intuition replaced by measurable standards.
- *Rising abstraction and symbolic mediation*: Innovations introduce new representational systems (writing, perspective, time measurement, computation), pushing humans toward abstract reasoning and symbolic manipulation rather than direct engagement.
- *Expansion of predictive and managerial competence*: Agriculture, timekeeping, and modern computing all enable anticipation and control of complex systems — emphasizing planning, modeling, and forecasting over reactive adaptation.
- *Institutionalization of expertise*: Knowledge gradually migrates from communal or craft contexts into specialized institutions — scribal schools, academies, universities, laboratories, and now algorithmic systems.
- *Standardization and professionalization*: Skills become formalized into disciplines, often validated through standardized procedures or credentials — e.g., the perspective grid, the engineer’s plan, the programmer’s code.

## Benefits and losses

Each new technology brought significant epistemic benefits to humanity; each innovation creates new epistemic infrastructures that expand horizons of thinking and enable knowledge to be scaled, formalized, or accelerated:

- *Durability and transferability of knowledge*: Technologies stabilize knowledge across time and space — from writing tablets to cloud storage — enabling cumulative cultural memory.
- *Precision and predictability*: Tools such as mechanical clocks and standardized measurement create epistemic reliability — the foundation for science, engineering, and bureaucracy.
- *Expansion of cognitive reach*: Fire extended the day; printing extended literacy; AI extends analytic scale — each enlarges the human cognitive envelope.
- *Democratization and communication*: Many technologies reduce entry barriers (e.g., alphabets, printing, smartphones), enabling broader participation in knowledge creation.
- *Integration and coordination*: Innovations improve collective synchronization — from time zones to networked data systems — fostering shared epistemic infrastructures.

At the same time, nearly every case shows how new technologies diminish earlier knowledge systems. Each innovation simplifies and narrows human interaction with the world, often leading to fragility or loss of embodied, tacit, or ecological knowledge:

- *Erosion of embodied, tacit, and local knowledge*: Each step toward abstraction reduces sensitivity to contextual, ecological, or bodily forms of knowing – the forager’s ecosystem, the artisan’s handicraft, the navigator’s intuition.
- *Cognitive dependence and deskilling*: Offloading tasks to tools (memory to writing, navigation to GPS, reasoning to AI) diminishes active cognitive capacities and resilience.
- *Centralization of epistemic authority*: Control over new media (scribes, printers, engineers, data scientists) concentrates power and legitimates specific knowledge regimes.
- *Reductionism and oversimplification*: Quantification, standardization, and algorithmic thinking filter out nuance – privileging what can be measured or codified.
- *Alienation and disconnection*: The replacement of communal or embodied practices with mediated ones (from the hearth to the screen) produces social and cognitive detachment.

Historical developments in technology reveal a consistent trade-off between abstraction and embodiment. Each leap forward externalizes thought, stabilizes knowledge, and extends cognitive power – yet it narrows the experiential, contextual, and communal dimensions of learning. The 21st-century phase marks the culmination of this long epistemic arc: intelligence increasingly resides in systems rather than in individuals, creating a civilization that knows ever more but understands ever less.

Table 4 summarizes our analysis of the benefits and losses of technological innovations.

Category	Common Benefits	Common Losses	Illustrative Cases
<b>Durability &amp; Transmission</b>	Knowledge preserved and extended beyond human lifespan	Loss of oral memory, experiential immediacy	Writing, Printing
<b>Precision &amp; Standardization</b>	Predictable measurement, shared baselines	Oversimplification, exclusion of qualitative nuance	Clocks, Engineering
<b>Expansion of Cognitive Reach</b>	Enhanced planning, forecasting, computation	Cognitive dependence, automation bias	Agriculture, AI
<b>Social Integration</b>	Wider access, collective coordination	Centralization of authority, epistemic inequality	Printing, Digital networks
<b>Symbolic Abstraction</b>	Creation of new representational languages (mathematics, code)	Alienation from embodied experience	Perspective, Computing

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**Table 4. Epistemic benefits and losses of technological innovations**

## Recurrent themes

In this section, we will discuss four major themes that run across our historical analysis of the patterns, benefits, and risks.

### Attention

Attention is a limited and effortful cognitive resource. Attentional fragmentation is the recurrent, rapid reallocation of limited cognitive resources across multiple streams of stimuli (notifications, feeds, apps, tabs, tasks). Classic cognitive theory holds that humans possess a finite capacity for sustained attention, which allows focus on a task or stimulus for only a limited period.<sup>8</sup> This capacity varies with task demands, motivation, interest, and prior experience.

<sup>8</sup> Kahneman, D. (1973). *Attention and effort*. Prentice-Hall.

However, the claim that recovery time equals interruption duration is contradicted by the scientific literature. Research shows recovery times are influenced by multiple factors beyond interruption length, and the widely-cited “23 minutes” figure represents an average recovery time that appears independent of how long the interruption itself lasted. It comes from Gloria Mark’s research but cannot be traced to published papers—only interviews. Duration is not the primary factor. The seminal 1989 study by Gillie & Broadbent explicitly found that interruption length did NOT affect recovery in the way the assertion claims. Instead, **complexity and similarity to the primary task were the key factors.**

The rapid rise of digital tools, particularly smartphones and social media, has introduced new challenges for maintaining sustained focus.<sup>9</sup> Research on digital distraction suggests that frequent media multitasking is associated with poorer sustained attention and greater susceptibility to interference.<sup>10</sup> Excessive smartphone use is associated with reduced attentional control, while social media platforms generate continuous streams of stimuli that encourage rapid attentional switching.<sup>11</sup>

Modern technologies amplify attentional scarcity by engineering ever-present, interruptive, and rewarding cues. Interface affordances such as push notifications, badges, infinite scroll, autoplay, and algorithmic feeds multiply external triggers. Even when notifications are ignored, their presence imposes a cognitive burden.<sup>12</sup> Experimental studies show that notification cues degrade performance on sustained-attention tasks, and that the mere presence of a smartphone reduces available working memory and fluid intelligence.<sup>13</sup>

Field experiments and diary studies demonstrate that external interruptions and self-interruptions fragment work into shorter episodes, increasing stress and

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<sup>9</sup> Shanmugasundaram, M., & Tamilarasu, A. (2023). The impact of digital technology, social media, and artificial intelligence on cognitive functions: A review. *Frontiers in Cognition*, 2, 1203077. <https://doi.org/10.3389/fcogn.2023.1203077>

<sup>10</sup> Ophir, E., Nass, C., & Wagner, A. D. (2009). Cognitive control in media multitaskers. *Proceedings of the National Academy of Sciences*, 106(37), 15583–15587. <https://doi.org/10.1073/pnas.0903620106>

<sup>11</sup> De-Sola Gutiérrez, J., Rodríguez de Fonseca, F., and Rubio, G. (2016). Cell-phone addiction: a review. *Front. Psychiatry* 7, 175. <https://doi.org/10.3389/fpsy.2016.00175>

<sup>12</sup> Ward, A. F., Duke, K., Gneezy, A., & Bos, M. W. (2017). Brain drain: The mere presence of one’s own smartphone reduces available cognitive capacity. *Journal of the Association for Consumer Research*, 2(2), 140–154. <https://doi.org/10.1086/691462>; Skowronek, J., Seifert, A., & Lindberg, S. (2023). The mere presence of a smartphone reduces basal attentional performance. *Scientific Reports*, 13(1), 9363. <https://doi.org/10.1038/s41598-023-36256-4>

<sup>13</sup> Stothart, C., Mitchum, A., & Yehnert, C. (2015). The attentional cost of receiving a cell phone notification. *Journal of Experimental Psychology: Human Perception and Performance*, 41(4), 893–897. <https://doi.org/10.1037/xhp0000100>

time-to-completion while reducing accuracy.<sup>14</sup> Media multitasking is associated with poorer filtering of irrelevant stimuli and increased distractibility, and neuroanatomical correlates have been reported in frequent multitaskers.<sup>15</sup> In educational and professional contexts, in-the-moment phone or social media use reduces task performance not only for users but also for nearby peers.<sup>16</sup>

The evidence, however, is nuanced. The impact on attention depends on applications rather than technology per se. Some activities, such as video gaming, have been shown to improve certain cognitive functions, including working memory, task switching, and attentional control.<sup>17</sup> Reviews suggest that excessive media multitasking is associated with increased distractibility, whereas specific forms of digital engagement may support attentional development.<sup>18</sup> Modern technologies thus create a high-frequency attentional ecology characterized by frequent task switching, shorter focus episodes, and greater reliance on shallow processing.

## Cognitive offloading

One of the most significant recurring phenomena across technological advancements is cognitive offloading: the transfer of memory, reasoning, and attention from the human mind to external supports. This began with writing systems, which externalized memory, and continues today with digital tools that externalize calculation, navigation, and even judgment. Although the concept of cognitive offloading has been introduced through the study of Internet use, the idea itself is not new. Philosophers and cognitive scientists have long argued that minds can extend into the world when external structures function like internal memory. This is the idea of the “extended mind,” a term coined in an influential paper by Clark and Chalmers in 1998.<sup>19</sup> The concept of the extended mind

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<sup>14</sup> Mark, G., Gudith, D., Klocke, U. (2008). The cost of interrupted work: more speed and stress. *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '08)*. 107–110. <https://doi.org/10.1145/1357054.1357072>

<sup>15</sup> Loh, K. K., & Kanai, R. (2014). Higher Media Multi-Tasking Activity Is Associated with Smaller Gray-Matter Density in the Anterior Cingulate Cortex. *PLoS ONE*, 9(9), e106698. <https://doi.org/10.1371/journal.pone.0106698>

<sup>16</sup> Kuznekoff, J. H. & Titsworth, S. (2013). The Impact of Mobile Phone Usage on Student Learning. *Communication Education*, 62(3), 233–252. <https://doi.org/10.1080/03634523.2013.767917>

<sup>17</sup> Sampalo, M., Lázaro, E., & Luna, P.-M. (2023). Action Video Gaming and Attention in Young Adults: A Systematic Review. *Journal of Attention Disorders*, 27(5), 530-538. <https://doi.org/10.1177/10870547231153878>

<sup>18</sup> Alho, K., Moissala, M., Salmela-Aro, K. (2022). Effects of Media Multitasking and Video Gaming on Cognitive Functions and Their Neural Bases in Adolescents and Young Adults. *European Psychologist*, 27(2). <https://doi.org/10.1027/1016-9040/a000477>

<sup>19</sup> Clark, A., & Chalmers, D. (1998). The extended mind. *Analysis*, 58(1), 7–19. <https://doi.org/10.1093/analys/58.1.7>

suggests that cognitive processes incorporate external tools and scaffolds, thereby extending the boundaries of the mind beyond biological brains. Modern digital offloading, in which phones, search engines, and apps become integrated components of our cognitive systems, has reinforced this concept.

Cognitive offloading refers to using actions or external tools to reduce the mental demands of a task, such as setting calendar reminders, saving notes to the cloud, using GPS, or even tilting one's head to read a rotated image. Instead of relying solely on internal memory, attention, and problem-solving, individuals delegate aspects of cognition to external bodies and artifacts. In seminal papers by Sparrow et al. and Risko and Gilbert, cognitive offloading is defined as the use of action to alter information-processing requirements, thereby reducing cognitive load.<sup>20</sup> Risko and Gilbert explain offloading through a metacognitive, cost–benefit lens: people offload when they judge that the environment can store or transform information more efficiently than their minds. Individuals estimate the costs (effort, error risk, anxiety, time) and benefits (accuracy, resource allocation) of internal versus external strategies and choose accordingly. Benefits are maximized when external stores are reliable and accessible, and when offloading removes interference. Costs arise when offloading reduces opportunities to encode structure or when ever-present devices consume residual attention. According to Risko and Gilbert, the use of internal and external resources is monitored and evaluated, resulting in future tendencies toward either strategy for particular tasks. Furthermore, they note that the deployment of external means can affect cognition, for instance, by reducing training in specific mental faculties.

Cognitive offloading primarily works by externalizing memory, recording information outside the brain for later retrieval. From clay tablets to notebooks and digital devices, humans have long externalized memory to manage complexity and ensure the persistence of knowledge beyond the limits of the biological brain. Modern technology amplifies this capacity: cloud storage, search engines, and note-taking apps form vast, searchable repositories that serve as extensions of individual and collective memory.<sup>21</sup>

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<sup>20</sup> Sparrow et al. (2011); Risko, E. F., & Gilbert, S. J. (2016). Cognitive offloading. *Trends in Cognitive Sciences*, 20(9), 676–688. <https://doi.org/10.1016/j.tics.2016.07.002> Cell

<sup>21</sup> Dror, I. E., & Harnad, S. (2008). Offloading cognition onto cognitive technology. In I. E. Dror & S. Harnad (Eds.). *How cognitive technology extends our minds* (pp. 1–23). John Benjamins Publishing Company. <https://doi.org/doi:10.1075/bct.16.02dro>

Cognitive offloading is associated with mnemonic benefits, including a phenomenon known as saving-enhanced memory.<sup>22</sup> Saving information externally is believed to reduce cognitive load and interference, thereby allowing the reallocation of mental resources to new tasks. Individual differences in working memory capacity modulate the extent to which people benefit from saving; individuals with higher working memory capacity show larger saving-enhanced memory gains.<sup>23</sup>

A review of studies on technology use and memory concluded that, taken together, there is convincing evidence that the Internet and other technologies can affect memory performance for specific tasks, such as remembering a route or a photographed item. However, the review also states that there is very little evidence that these technologies are causing a broader decline in memory, that the Internet or computers are “killing” or “ruining” memory.<sup>24</sup>

Cognitive offloading should not be regarded as intrinsically problematic. As the great British philosopher and mathematician Alfred North Whitehead observed, “Civilization advances by extending the number of important operations which we can perform without thinking about them.”<sup>25</sup> Cognitive offloading is a genuine achievement of technological progress, reducing cognitive load and relieving humans of mechanical calculation or spatial reasoning. It is difficult to imagine functioning in modern societies without the capacity to externalize memory and manipulate environments to reduce cognitive demands.

Developmental psychological evidence shows that humans manipulate their environment to reduce computational demands from an early age.<sup>26</sup> Young children evaluate the difficulty and value of a task when deciding whether to offload.<sup>27</sup> Cognitive

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<sup>22</sup> Storm, B. C., & Stone, S. M. (2015). Saving-enhanced memory: The benefits of saving on the learning and remembering of new information. *Psychological Science*, 26(2), 182–188.

<https://doi.org/10.1177/0956797614559285>; Runge, Y., Mogessie, M., & Buchner, A. (2023). The saving-enhanced memory effect can be observed when only part of information is saved. *Memory & Cognition*, 51(8), 1981–1996. <https://doi.org/10.3758/s13421-024-01545-4>

<sup>23</sup> Buchli, D. R., & Storm, B. C. (2025). Working memory capacity and the saving-enhanced memory effect. *Memory*, 33(8), 1015–1030. <https://doi.org/10.1080/09658211.2025.2551230>

<sup>24</sup> Schacter, D. L. (2022). Media, technology, and the sins of memory. *Memory, Mind & Media*, 1, e1. <https://doi.org/10.1017/mem.2021.3>

<sup>25</sup> [https://en.wikiquote.org/wiki/Alfred\\_North\\_Whitehead](https://en.wikiquote.org/wiki/Alfred_North_Whitehead)

<sup>26</sup> Armitage, K. L., Bulley, A., & Redshaw, J. (2020). Developmental origins of cognitive offloading. *Proceedings of the Royal Society B: Biological Sciences*, 287(1928), 20192927.

<https://doi.org/10.1098/rspb.2019.2927>

<sup>27</sup> Dong, X., Liu, Y., & Lu, H. J. (2022). Effects of learning item difficulty and value on cognitive offloading during middle childhood. *Metacognition and Learning*, 17, 1097–1115.

<https://doi.org/10.1007/s11409-022-09309-8>

offloading thus appears to be a natural human capability that is amplified, rather than created, by technology.

However, the growing literature on the costs of cognitive offloading, for example, for performance on memory-based tasks, should be taken seriously.<sup>28</sup> Extraneous cognitive load acts as a triple barrier: (1) It prevents information from entering working memory, (2) it inhibits information from being stored in long-term memory, and (3) it can prevent learners from externalizing information using technology.<sup>29</sup>

## Tacit knowledge

Each technological breakthrough brings gains in abstraction and precision, but often at the cost of tacit, embodied, local, and experiential knowledge. The transition from oral to written culture weakened memory and improvisation; industrialization displaced craft skills; digital technologies are now automating intuition and pattern recognition.

The concept of tacit knowledge is rooted in the work of Michael Polanyi, who emphasized the importance of knowledge acquired through practice and experience.<sup>30</sup> Tacit knowledge is essential for human cognition and behavior, as well as for social cohesion and cultural transmission. Pattern recognition, embodied perception, intuitive action selection, and non-verbal social interpretation rely on forms of knowledge that cannot be reduced to explicit rules. Expertise, in particular, entails a transition from explicit reasoning to rapid, intuitive, perception-based decision-making.<sup>31</sup> Research across psychology and organizational science confirms that tacit knowledge expands with experience. Its transfer typically requires hands-on practice, mentorship, and repeated exposure rather than written instructions—a point underscored in recent studies of organizational learning and performance.<sup>32</sup> In professional contexts such as medicine, engineering, or science, experts routinely rely on “feel,” judgment, and embodied skill. Recent research emphasizes that organizations perform better when

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<sup>28</sup> Richmond, L. L., & Taylor, R. G. (2025). The benefits and potential costs of cognitive offloading for retrospective information. *Nature Reviews Psychology*, 4(5), 312–321.

<https://doi.org/10.1038/s44159-025-00432-2>; Grinschgl, S., Papenmeier, F., & Meyerhoff, H. S. (2021). Consequences of cognitive offloading: Boosting performance but diminishing memory. *Quarterly Journal of Experimental Psychology*, 74(9), 1477-1496. <https://doi.org/10.1177/17470218211008060>

<sup>29</sup> Skulmowski, A. (2023). The Cognitive Architecture of Digital Externalization. *Educational Psychology Review*, 35(4), 101. <https://doi.org/10.1007/s10648-023-09818-1>

<sup>30</sup> Polanyi, M. (1966). *The Tacit Dimension*. Chicago/London: The University of Chicago Press.

<sup>31</sup> DeDeo, S., & Miton, H. (2022). The cultural transmission of tacit knowledge. *Journal of the Royal Society Interface*, 19(191), 20220238. <https://doi.org/10.1098/rsif.2022.0238>

<sup>32</sup> Zia, U., Zhang, J., & Alam, S. (2023). Role of tacit knowledge management process and innovation capability for stimulating organizational performance: empirical analysis, PLS-SEM approach. *Kybernetes*, 53(11), 4976–5000. <https://doi.org/10.1108/K-03-2023-0444>

organizational mechanisms support tacit knowledge sharing. Psychological factors such as trust, psychological capital, and task interdependence significantly influence the exchange of tacit knowledge that fuels innovation.<sup>33</sup>

Tacit knowledge is in itself a major driver of technological innovation. Although technologies often erode tacit knowledge, they are also essential to innovation.<sup>34</sup> Empirical studies show that both incremental and breakthrough innovations depend heavily on the exchange of tacit knowledge within teams.<sup>35</sup> Joel Mokyr's historical analysis of the Industrial Revolution highlights the interaction between propositional knowledge and prescriptive, practice-based knowledge.<sup>36</sup> Formal scientific understanding alone was insufficient without skilled practitioners capable of translating ideas into functioning technologies. Tacit knowledge also shapes the geography of innovation. Urban and regional studies indicate that technological clusters emerge in part because tacit knowledge is more easily transmitted through physical proximity, informal networks, and shared work practices.<sup>37</sup> Conversations, lab culture, and apprenticeships often transmit more actionable know-how than formal documentation.

Technological innovations have repeatedly weakened tacit knowledge by codifying and automating tasks that once required experiential judgment. Digital technologies reduce reliance on embodied experience, substituting physical interaction with virtual interaction. This risks eroding forms of tacit knowledge grounded in touch, physical manipulation, direct perception, and situational awareness. At the same time, new technological contexts generate new forms of tacit knowledge. Navigating complex digital systems, interpreting algorithmic outputs, and collaborating in hybrid environments require experience-based judgment that cannot be fully codified.

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<sup>33</sup> Hu, R., Li, Y., Huang, J., Zhang, Y., & Jiang, R. (2023). Psychological capital and breakthrough innovation: The role of tacit knowledge sharing and task interdependence. *Frontiers in Psychology*, 14, 1097936. <https://doi.org/10.3389/fpsyg.2023.1097936>

<sup>34</sup> Senker, J. (1995). Tacit Knowledge and Models of Innovation. *Industrial and Corporate Change*, 4(2), 425–447. <https://doi.org/10.1093/icc/4.2.425>

<sup>35</sup> Houessou, A. M., Aoudji, A. K. N., Biao, G., & Floquet, A. (2023). Tacit knowledge acquisition and incremental innovation capability: Proximity perspective. *Journal of Open Innovation: Technology, Market, and Complexity*, 100085. <https://doi.org/10.1016/j.joitmc.2023.100085>

<sup>36</sup> Mokyr, J. (2002). *The Gifts of Athena: Historical Origins of the Knowledge Economy*. Princeton University Press; Mokyr, J. (2005). The Intellectual Origins of Modern Economic Growth. *The Journal of Economic History*, 65(2), 285–351. <https://doi.org/10.1017/S0022050705000112>.

<sup>37</sup> Petralia, S., Kemeny, T., & Storper, M. (2023). The transformative effects of tacit technological knowledge. *Working Paper*, Utrecht University / UCLA / LSE. [https://eprints.lse.ac.uk/120154/1/III\\_working\\_paper\\_103.pdf](https://eprints.lse.ac.uk/120154/1/III_working_paper_103.pdf)

# Adaptability

Across historical episodes of technological change, societies have faced the challenge of adjusting to shifting tools, tasks, and forms of work. In contemporary AI-driven contexts, this challenge has intensified. Rapid tool cycles, unstable task boundaries, and pervasive uncertainty require individuals to revise strategies in real time and continually update competencies. As a result, adaptability—defined as the ability to adjust one’s thinking and behavior flexibly in response to changing conditions—has become a foundational epistemic skill rather than a peripheral “soft skill.”

Adaptability refers to the capacity to adjust thinking and behavior flexibly in response to changing conditions. It has become increasingly central as routine cognitive operations are automated and non-routine problem-solving grows in importance. Empirical evidence links adaptability to employability, psychological well-being, and effective participation in dynamic environments.<sup>38</sup>

Adaptability is not a fixed trait. Cognitive neuroscience and learning science show that adaptive behavior is grounded in neural plasticity.<sup>39</sup> Cognitive flexibility—the ability to shift perspectives, strategies, or task sets—is particularly sensitive to experience and training. Adaptation involves a balance between exploration and exploitation. Excessive switching without consolidation can undermine learning, while rigid optimization for stable conditions leads to brittleness. Productive adaptability depends on environments that combine stability with variation and allow for revision.

Developmental evidence indicates that adolescence is a critical period for the maturation of executive functions related to flexibility and control.<sup>40</sup> Cognitive flexibility continues to develop into early adulthood, making middle and secondary schooling critical periods for the development of adaptive capacity. Adaptability is also central to lifelong learning. In rapidly changing technological environments, individuals must repeatedly re-enter learning cycles, update their domain knowledge, and recalibrate their judgments. Historical evidence suggests that societies and institutions that fail to support adaptability experience widening epistemic inequality and accelerated deskilling.<sup>41</sup>

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<sup>38</sup> World Economic Forum. (2023). *The Future of Jobs Report 2023*. World Economic Forum. <https://www.weforum.org/reports/the-future-of-jobs-report-2023>

<sup>39</sup> Dehaene (2020).

<sup>40</sup> Casey, B. J., Jones, R. M., & Hare, T. A. (2008). The adolescent brain. *Annals of the New York Academy of Sciences*, 1124, 111–126. <https://doi.org/10.1196/annals.1440.010>; Luna, B., et al (2015). An integrative model of the maturation of cognitive control. *Annual review of neuroscience*, 38, 151–170. <https://doi.org/10.1146/annurev-neuro-071714-034054>

<sup>41</sup> van Bavel, B., Curtis, D. R., & Soens, T. (2018). Economic inequality and institutional adaptation in response to flood hazards: a historical analysis. *Ecology and Society*, 23(4).

# Implications for education

## Layers of cognitive competence

Across history, major technological innovations—from writing and printing to digital media and artificial intelligence—have not merely added new tools to education. They have restructured the ecology of knowledge itself, altering which human capacities are exercised, which are displaced, and which become newly critical. Contemporary debates about smartphones or AI in education echo earlier concerns about calculators, computers, or mass media, yet **history shows that the central challenge is not technological novelty but educational rebalancing.**

To guide this rebalancing, we might consider a five-layer framework of cognitive competence. The framework analytically distinguishes among different types of human cognitive capabilities, which are affected differently by technological change. **Its purpose is not to organize education to resist technology, but to help education systems decide what must be preserved, what can be delegated, what should be strengthened, and what must be newly taught.**

## Foundational human capacities

**The first layer consists of foundational human capacities: attention regulation, memory formation, spatial and temporal orientation, causal reasoning, and language comprehension.** These capacities are biologically grounded and developmentally acquired, and they underpin all higher-order learning.<sup>42</sup>

*Historically, these capacities are the most vulnerable to technological displacement.* Writing externalized memory, mechanical clocks abstracted lived time into uniform units, GPS systems outsourced spatial navigation, and contemporary AI systems increasingly externalize explanation and linguistic production. Although such technologies often improve efficiency, they reduce the need to exercise foundational capacities in everyday life. When these capacities are weakened, higher-level learning becomes fragile, regardless of the quality of curriculum content.

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<https://doi.org/10.5751/ES-10491-230430>; Brugger, F., Gehrke, C. Skilling and deskilling: technological change in classical economic theory and its empirical evidence. *Theory and Society*. 47, 663–689 (2018).

<https://doi.org/10.1007/s11186-018-9325-7>

<sup>42</sup> Dehaene, S. (2020). *How We Learn. Why Brains Learn Better Than Any Machine... for Now*. Viking.

From an educational perspective, these capacities remain non-delegable. Even when technologies can substitute for them functionally, they remain essential for understanding, judgment, error detection, and autonomy. Learners who no longer need to remember, attend, or reason to function may still require these capacities to evaluate information, resolve conflicts between systems, or act responsibly when technological supports fail. *Education, therefore, has a protective and developmental role: it must deliberately cultivate foundational capacities that technological environments no longer reliably train.*<sup>43</sup>

A simple classroom example is device-free reading and recall, followed by a short reflective writing task: learners read a text without digital interruptions, then reconstruct key ideas from memory and articulate their understanding, strengthening attention, encoding, and comprehension.

## Procedural and instrumental skills

**The second layer comprises procedural and instrumental skills: routinized techniques such as calculation, transcription, classification, searching, and the execution of standardized procedures.** These skills have historically been the primary targets of automation.

Scripts and the printing press reduced the need for memorization; calculators displaced manual arithmetic; word processors replaced many aspects of handwriting and grammar-checking; and AI systems now automate drafting, summarization, translation, and coding.<sup>44</sup> Unlike foundational capacities, *procedural skills are often safely delegable, and their automation has frequently enabled social and economic progress. However, technology can also produce deskilling if learners bypass practice and never develop fluency or error sensitivity.*

The educational risk here lies at two extremes. On one hand, premature or unreflective offloading can weaken conceptual understanding if learners never grasp what procedures do or why they work.<sup>45</sup> On the other hand, over-preservation of obsolete

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<sup>43</sup> Armitage, K. L., & Gilbert, S. J. (2025). The nature and development of cognitive offloading in children. *Child Development Perspectives*, 19, 108–115. <https://doi.org/10.1111/cdep.12532>

<sup>44</sup> Autor, D. H., Levy, F., & Murnane, R. J. (2003). The Skill Content of Recent Technological Change: An Empirical Exploration\*. *The Quarterly Journal of Economics*, 118(4), 1279–1333. <https://doi.org/10.1162/003355303322552801>; OECD (2021). *AI and the Future of Skills, Volume 1: Capabilities and Assessments*, Educational Research and Innovation, OECD Publishing, Paris, <https://doi.org/10.1787/5ee71f34-en>.

<sup>45</sup> Kirschner, P. A., & de Bruyckere, P. (2017). The myths of the digital native and the multitasker. *Teaching and Teacher Education*, 67, 135–142. <https://doi.org/https://doi.org/10.1016/j.tate.2017.06.001>

procedures can crowd out higher-order learning and entrench inequities by turning outdated skills into gatekeepers. *The policy challenge is therefore not whether to automate, but how to align automation with conceptual understanding.*

Education should strategically automate, retaining procedural practice where it supports conceptual understanding and independent capability, while allowing tools to reduce unnecessary cognitive load. A telling classroom example is solving equations fluently before using a calculator or CAS tool: students first practice core transformations by hand to build procedural confidence and error detection, and only then use technology to extend the range of problems they can explore.

## Conceptual and structural understanding

**The third layer is conceptual and structural understanding: grasping underlying principles, causal mechanisms, systems, models, and abstractions. This layer includes systems thinking, explanatory reasoning, transfer across contexts, and the ability to connect representations to real-world phenomena.**

*Historically, this layer has often been expanded—rather than diminished—by technology, provided that education systems adapt. Agricultural technologies fostered calendrical reasoning and prediction; civil engineering cultivated geometry and systems thinking; chemistry trained mechanistic explanation and experimental reasoning; computing introduced modeling and simulation as central epistemic practices.<sup>46</sup> As routine procedures become automated, the opportunity arises to focus education more deeply on structure, explanation, and interpretation.<sup>47</sup>*

Educational systems frequently fail to capitalize on this opportunity. Curricula often retain procedural mastery as a proxy for rigor, even after those procedures lose practical relevance. The historical lesson is clear: *when tools become more powerful, educational **depth** must increase, not simply speed or volume. Conceptual understanding becomes the primary locus of durable competence.<sup>48</sup>*

Education should therefore make conceptual explanation and transfer the primary growth target, explicitly shifting emphasis from producing correct outputs to understanding systems and reasoning. A classroom example is asking students to

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<sup>46</sup> Holmes, W., Bialik, M., & Fadel, C. (2019). *Artificial Intelligence in Education: Promises and Implications for Teaching and Learning*. Center for Curriculum Redesign.

<sup>47</sup> Fadel, C. et al. (2024). *Education for the Age of AI: Why, What, and How Should Students Learn?* Center for Curriculum Redesign.

<sup>48</sup> Butcher, K. R. (2024). Promoting understanding in digital contexts: using the construction-integration model as a framework for educational technology design and assessment. *Discourse Processes*, 61(6–7), 347–351. <https://doi.org/10.1080/0163853X.2024.2357983>

explain why a mathematical procedure works and apply it to a novel problem: rather than repeating a learned method, students justify the method’s logic and demonstrate transfer to a new context, showing that they understand the structure rather than merely following steps.

## Integrative sense-making

**The fourth layer is integrative sensemaking, leading to cross-domain expertise and eventually wisdom.<sup>49</sup> It concerns the ability to connect and transfer knowledge across contexts: building structured breadth, recognizing deep patterns, transferring frameworks across fields, and choosing the right conceptual lens for complex problems.**

Generative systems can produce plausible outputs within domains, but humans remain crucial for setting direction, integrating knowledge across disciplines, making principled trade-offs, detecting category errors, and transferring insights to new contexts.

Technology can assist by making cross-domain information more accessible and by generating alternative framings, but it can also encourage shallow, overgeneralized thinking if learners rely on surface-level summaries rather than developing coherent models. Education should therefore cultivate cross-domain transfer and structured breadth, helping learners develop mental “bridges” between disciplines and the ability to reason across systems.

A classroom example is asking students to compare climate, health, and financial systems using the same feedback-loop model: learners apply a shared conceptual structure (e.g., reinforcing versus balancing loops) across these domains, demonstrating that they can recognize patterns and build coherence beyond a single subject area.

## Epistemic meta-competence

The fifth and final layer, and **the most critical in contemporary contexts, is epistemic meta-competence. This includes the ability to evaluate knowledge claims, assess sources and provenance, detect error and bias, calibrate trust, and supervise the outputs of technical systems.<sup>50</sup>** This layer monitors all other layers (including

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<sup>49</sup> See Chapter 3 in Fadel et al. (2024).

<sup>50</sup> Risko, E. F., & Kelly, M. O. (2023). Thinking in the digital age: Everyday cognition and the dawn of a new age of metacognition research. *Applied Cognitive Psychology*, 37(4), 785–788.  
<https://doi.org/https://doi.org/10.1002/acp.4102>

integration); it handles uncertainty, reliability, and accountability; and it is where AI-era demands become most visible (verification, calibration, epistemic vigilance).

Epistemic meta-competence includes the capability of:

- monitoring and regulating one's knowledge practices,
- calibrating confidence and uncertainty,
- deciding when to rely on tools vs internal reasoning,
- understanding error modes and accountability,
- supervising AI-supported cognition.

As technologies grow more complex and opaque, *epistemic authority increasingly shifts away from direct human experience toward instruments, infrastructures, and algorithms*. Each major information technology has generated new demands at this level: print requires source criticism; photography requires visual literacy; the internet demands information evaluation; social media intensifies lateral reading; and AI systems now require users to judge fluent but potentially unreliable outputs.<sup>51</sup>

In the age of generative AI, epistemic meta-competence becomes a core capability, enabling epistemic governance.<sup>52</sup> **The central divide is no longer between those who use advanced tools and those who do not, but between those who can critically orchestrate them and those who must defer to them.** Without explicit educational attention to this layer, technological empowerment risks becoming a form of epistemic impoverishment and dependency.

Education should therefore teach epistemic judgment explicitly as a core civic competence, embedding verification, sourcing, and reasoning about reliability across subjects. A strong classroom example is having students fact-check an AI-generated answer using primary sources and justify confidence: learners compare the output with trusted evidence, identify gaps or errors, and explain the basis for accepting, revising, or rejecting the claim.

Figure 1 summarizes the five-layered framework of cognitive capabilities and the role education could play in each of the five layers. The framework distinguishes the five interacting layers of human cognitive competence. Historical technological change tends to displace activity in the lower layers—particularly procedural skills and, indirectly, foundational capacities—while increasing the importance of conceptual

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<sup>51</sup> McGrew, S. (2024). Teaching lateral reading: Interventions to help people read like fact checkers. *Current Opinion in Psychology*, 55, 101737. <https://doi.org/https://doi.org/10.1016/j.copsyc.2023.101737>; Pareek, S., van Berkel, N., Velloso, E., & Goncalves, J. (2024). Effect of Explanation Conceptualisations on Trust in AI-assisted Credibility Assessment. *Proc. ACM Hum.-Comput. Interact.*, 8(CSCW2). <https://doi.org/10.1145/3686922>

<sup>52</sup> Fadel et al. (2024).

understanding and epistemic judgment. The right-hand columns translate the framework into practice by specifying, for each layer, what education should prioritize and providing a short classroom example. Together, the framework and examples support curriculum, assessment, and policy design aimed at sustaining human agency and deep learning in technologically saturated environments.

### Five-Layer Framework of Educational Competence

<b>Layer 5: Epistemic meta-competence</b> Judgement, verification, AI supervision, knowing when not to trust	<b>What education should do</b> Teach explicitly (core civic skill)	<b>Classroom example</b> Students fact-check an AI-generated answer using primary sources and justify confidence.
<b>Layer 4: Integrative sensemaking</b> Cross-domain transfer, structured breadth, pattern recognition across fields	<b>What education should do</b> Build integrative sensemaking	<b>Classroom example</b> Students compare climate, health and finance systems using the same feedback-loop model.
<b>Layer 3: Conceptual &amp; structural understanding</b> Models, causal explanation, abstraction, transfer within domains	<b>What education should do</b> Deepen understanding (primary target)	<b>Classroom example</b> Students explain why a math procedure works and apply it to a novel problem.
<b>Layer 2: Procedural &amp; instrumental skills</b> Calculation, drafting, searching, routine execution (automatable)	<b>What education should do</b> Strategically automate (with grounding)	<b>Classroom example</b> Students practice solving equations fluently before using a calculator or CAS tool.
<b>Layer 1: Foundational human capacities</b> Attention, memory formation, spatial & temporal orientation	<b>What education should do</b> Preserve & cultivate (non-delegable)	<b>Classroom example</b> Students do device-free reading and recall, followed by a short written reflection.

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Figure 1. Five-layer framework

## Educational answers to the historical patterns

We refer to the key historical patterns in the epistemic impact of technologies, as discussed [above](#) and in Table 3. Table 5 complements this analysis by adding suggestions for educational practice and policy.

Education must actively guide transitions caused by technological innovations, ensuring that the delegation of procedural and instrumental skills does not hollow out understanding. Rather than preserving outdated routines as curricular gatekeepers, education systems need to shift emphasis upward—towards conceptual and structural understanding—so that learners grasp the principles, models, and systems that

underpin automated outputs. Equally important is the explicit cultivation of epistemic judgement: learners must be taught how knowledge claims are produced, validated, and limited, especially as epistemic authority moves from direct experience toward instruments, platforms, and algorithms. In this sense, education’s task is to sustain epistemic autonomy in the face of technological dependency.

Pattern	Educational practice	Educational policy
Expansion & narrowing	Compensate for eroded capacities	Avoid narrow skill policies
Externalization of cognition	Shift focus to supervision	Invest in higher-order skills
Situated to standardized knowledge	Teach limits of models	Balance standardization
Redefinition of authority	Explain how authority is produced	Transparency requirements
Selective deskilling	Guide reskilling upward	Support transitions
Epistemic opacity	Teach vigilance & checking	Resilience & safeguards
Compression of time & learning	Slow learning where needed	Protect depth & reflection
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**Table 5. Key historical patterns and their significance for education**

From a policy perspective, these historical patterns imply that skill strategies focused narrowly on “future skills” or tool-specific competencies are structurally insufficient. Policies must instead address how technologies redistribute cognitive labor, authority, and risk across society. This requires investing in higher-order capabilities—such as evaluation, supervision, and error detection—while also protecting time and space for deep learning, reflection, and consolidation in increasingly accelerated, compressed knowledge environments. *Policymakers should anticipate uneven transitions and new forms of inequality, as selective deskilling and rising epistemic opacity tend to advantage those with stronger conceptual and meta-epistemic capacities.* Transparency requirements, curriculum reform, teacher professional development, assessment redesign, and final evaluations (Baccalaureates, etc.) are therefore not peripheral concerns but central levers of resilience. Ultimately, **the historical lesson is that education policy cannot be technologically neutral: it must actively shape how societies remain capable of understanding, questioning, and governing the systems on which they increasingly rely.**

## Educational implications of the key cognitive challenges

As we have seen, historical analyses of the impact of technological innovations on human cognition have identified four recurring dynamics that are particularly consequential for education: cognitive offloading, attention, tacit knowledge, and adaptability. These themes capture how technologies redistribute cognitive effort between humans and external systems, how they reshape the conditions for sustained learning, how they affect embodied and experiential forms of knowing, and how they alter the capacity to cope with ongoing change. Importantly, each theme entails both gains and risks. These themes converge on a common educational challenge: technological environments increasingly optimize for efficiency, speed, and external support, while education remains responsible for sustaining the internal capacities that enable understanding, judgment, and autonomy.

Table 6 synthesizes these four cognitive dynamics from an educational perspective. For each theme, it identifies the core educational risk, the corresponding educational response, and the implications for practice and policy.

Theme	Core educational risk	Key educational response	Implications for practice & policy
<b>Attention</b>	Fragmentation reduces sustained focus and deep learning	Treat attention as a trainable capacity	Design distraction-aware learning environments
<b>Cognitive offloading</b>	Over-reliance on external tools weakens internal encoding and reasoning	Teach intelligent reliance and metacognitive control	Embed information literacy, reflection, and AI supervision
<b>Tacit knowledge</b>	Loss of embodied, experiential forms of knowing	Reinforce learning through practice and embodiment	Expand experiential and apprenticeship-based pedagogy
<b>Adaptability</b>	Brittle skills in rapidly changing contexts	Cultivate flexibility and learning-to-learn	Assess processes and support lifelong learning

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**Table 6. Key recurrent themes and their educational implications**

## Attention as an educational resource

Attention is the gateway to learning, but is often destabilized by distractors in the environment, not at least by technological devices.<sup>53</sup> Attentional fragmentation is not simply an individual failure of self-control, but a structural feature of modern digital environments. Notification systems, feeds, and multitasking affordances systematically increase task-switching and reduce opportunities for sustained engagement. Research shows that even passive exposure to such cues degrades working memory, learning quality, and task performance, particularly in educational settings.

Many education systems have responded to concerns about attentional fragmentation by restricting or banning the use of smartphones and social media for children in school settings, and by taking broader policy actions. A growing number of countries, including France, Chile, Brazil, Hungary, the Netherlands, Belgium, and China, have introduced laws or school-level policies that ban or severely restrict smartphone use during class time to reduce distractions and help students focus on learning instead of constant alerts and social feeds. Several U.S. states and school districts similarly require phones to be turned off and stored out of sight during instructional hours, and some schools use dedicated “phone hotels” or apps that block social media access during the school day.

Beyond school walls, age-based restrictions on social media access have gained traction in government policy discussions; for instance, Australia is implementing a ban on social media for children under 16. Very recently, the French public health agency published a comprehensive scientific report on the risks posed by social media to the health of 11- to 17-year-olds, recommending limits on children’s access to these platforms.<sup>54</sup>

However, the scientific community is not in complete consensus on the need for very restrictive measures.<sup>55</sup> The evidence on smartphone bans in schools is mixed.<sup>56</sup> Smartphone bans have a significant but modest effect, with a greater impact on social

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<sup>53</sup> Van Damme, D. and Fadel, C. (2025). *Executive Functions Conceptual Framework and Relevance for Education*. Center for Curriculum Redesign.

<https://curriculumredesign.org/wp-content/uploads/Executive-Functions-CCR.pdf>

<sup>54</sup> Anses. (2025). *Usages des réseaux sociaux numériques et santé des adolescents*. (autosaisine n° 2019-SA-0152). Maisons-Alfort : Anses. <https://www.anses.fr/system/files/AP2019-SA-0152-RA.pdf>

<sup>55</sup> Goodyear, V. A., James, C., Orben, A., Quennerstedt, M., Schwartz, G., & Pallan, M. (2025). Approaches to children’s smartphone and social media use must go beyond bans. *BMJ*, 388, e082569.

<https://doi.org/10.1136/bmj-2024-082569>

<sup>56</sup> Campbell, M., Edwards, E. J., Pennell, D., Poed, S., Lister, V., Gillett-Swan, J., Kelly, A., Zec, D., & Nguyen, T.-A. (2024). Evidence for and against banning mobile phones in schools: A scoping review. *Journal of Psychologists and Counsellors in Schools*, 34(3), 242-265. <https://doi.org/10.1177/20556365241270394>

well-being than on academic performance.<sup>57</sup> Research among teachers and students indicates that both favored regulating students' phone use at the school level, but were less in favor of a total ban.<sup>58</sup> Therefore, these measures are often paired with digital literacy and media education initiatives that teach students to manage attention and use technology responsibly, reflecting a broader shift away from simply removing distractions toward building skills for sustained focus and healthy technology habits.

Education must treat attention as a trainable and protectable capacity, rather than an assumed background condition. This has implications at multiple levels. At the pedagogical level, learning activities should be designed to support sustained focus and deep engagement, rather than constant interruption. At the institutional level, norms around device use, classroom design, and scheduling can either amplify or mitigate attentional fragmentation. At the policy level, educational quality frameworks should explicitly recognize attentional conditions as part of the learning environment. Protecting attention is not about just banning technology, but about creating contexts in which meaningful learning remains cognitively possible.

## From cognitive offloading to intelligent reliance

Cognitive offloading is neither new nor inherently problematic. Humans have always used external structures to reduce cognitive load, from writing and diagrams to calculators and maps. What distinguishes contemporary digital offloading is its scale, immediacy, and pervasiveness. Memory, search, navigation, and even explanation are now continuously available, reliable, and low-cost. As a result, learners increasingly operate in environments with weak incentives to internalize information or develop durable mental models.

The educational implication is not to resist offloading, but to teach intelligent reliance. In his seminal paper on cognitive offloading, Skulmowski explicitly recommends that educational approaches should “maximize the meaningfulness of the residual information” retained during cognitive offloading.<sup>59</sup> However, he also warns that offloading can lead to retaining only “the gist of information” or its location, potentially creating an “illusion of having memorized” content. This underscores the need for “intelligent” rather than indiscriminate reliance on external cognitive tools.

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<sup>57</sup> Böttger, T., & Zierer, K. (2024). To Ban or Not to Ban? A Rapid Review on the Impact of Smartphone Bans in Schools on Social Well-Being and Academic Performance. *Education Sciences*, 14(8), 906.

<https://doi.org/10.3390/educsci14080906>

<sup>58</sup> Gath, M. E., Monk, L., Scott, A., & Gillon, G. T. (2024). Smartphones at School: A Mixed-Methods Analysis of Educators' and Students' Perspectives on Mobile Phone Use at School. *Education Sciences*, 14(4), 351.

<https://doi.org/10.3390/educsci14040351>

<sup>59</sup> Skulmowski (2023).

Learners must develop metacognitive awareness of *when* offloading is beneficial and *when* it undermines understanding. Education can no longer equate competence with possession of information; instead, it must cultivate meta-knowledge: the ability to locate, evaluate, integrate, and critically use external information sources. This includes explicit instruction in information literacy, reflection on how technologies shape cognition, and deliberate practice in deciding when to rely on tools and when to internalize skills. Without such guidance, offloading risks turning from cognitive support into epistemic dependency.

Education seems to be quite effective in mitigating the cognitive risks of offloading. Gerlich found evidence that individuals with advanced educational backgrounds maintained robust critical thinking skills despite regular AI usage.<sup>60</sup> Education, whether explicitly or implicitly, fosters critical evaluation skills. The curriculum should include explicit instruction in evaluating AI-generated content critically. Education should also promote reflective practices that encourage individuals to regularly assess their dependence on AI and its influence on their cognitive processes.

However, artificial intelligence might represent a qualitative step beyond cognitive offloading to outsourcing. In a recent blog post, the Dutch educational psychologist Paul Kirschner distinguishes the two: “With offloading, you still think, and the artefact (tool) supports you. With outsourcing, the system thinks, and you consume the result. That distinction matters. (...) There’s therefore a crucial difference between using AI to support thinking and using it to substitute for thinking. (...) Offloading supports cognition. Outsourcing replaces it.”<sup>61</sup> Educators and students need to be aware of that distinction and reinforce metacognitive control to make deliberate decisions about offloading or outsourcing cognitive operations.<sup>62</sup>

## Reclaiming tacit knowledge

Technological progress repeatedly trades experiential, embodied, and intuitive forms of knowledge for abstraction, codification, and automation. While this enables scale and precision, it also weakens tacit knowledge—forms of knowing that are acquired through practice, immersion, and social interaction rather than explicit instruction. Such knowledge underpins expertise, innovation, and effective action in uncertain environments. Educational systems risk undervaluing tacit knowledge because it is

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<sup>60</sup> Gerlich (2025). See also: Bandam, R. (2025). *Cognitive Offloading: How AI is Quietly Eroding Our Critical Thinking*. <https://www.computer.org/publications/tech-news/trends/cognitive-offloading>

<sup>61</sup> <https://www.kirschnered.nl/2026/01/13/understanding-ai-offloading-or-outsourcing-thinking/>

<sup>62</sup> Gilbert, S. J. (2024). Cognitive offloading is value-based decision making: Modelling cognitive effort and the expected value of memory. *Cognition*, 247, 105783. <https://doi.org/https://doi.org/10.1016/j.cognition.2024.105783>

difficult to formalize and assess. Yet the evidence is clear that high-level competence depends on it. The implication is that education must deliberately preserve and cultivate experiential learning, particularly as digital tools reduce everyday exposure to real life experience.

One reason education should foster tacit knowledge is that it underpins expert performance across domains. Studies of expertise consistently show that high-level competence depends on pattern recognition, embodied anticipation, and intuitive decision-making, none of which can be fully captured in explicit rules.<sup>63</sup> These abilities are cultivated through practice, not solely through theoretical instruction. Education must therefore counterbalance growing technological dependence by ensuring that students build the internal, experiential resources needed for autonomous judgment.

Moreover, tacit knowledge is crucial for innovation. Knowledge-creation breakthroughs often emerge from the interaction of tacit and explicit knowledge rather than from codified information alone. Skills such as improvisation, tinkering, and rapid problem-solving depend on sensory engagement, hands-on experimentation, and informal social learning—conditions that digital environments cannot fully replicate. By cultivating tacit knowledge, education equips learners not only to consume information but also to transform it into new ideas, methods, and artifacts.

Human learning is deeply embodied and social. Embodied cognition research demonstrates that perception, movement, and physical interaction significantly influence how people understand and remember.<sup>64</sup> Similarly, tacit knowledge often spreads through apprenticeship-like social processes—observation, imitation, and shared practice—rather than through textual transmission. Digital learning can supplement but cannot replace these interpersonal dynamics. Education systems that want to preserve deep learning must therefore incorporate collaborative, physical, and experiential modes of engagement.

Finally, modern technologies create new contexts in which tacit knowledge is increasingly essential. Navigating complex digital systems, assessing online information, interpreting algorithmic recommendations, and collaborating in hybrid environments all demand subtle, experience-based judgment.<sup>65</sup> These forms of “digital tacit knowledge” are challenging to teach explicitly but are vital for functioning effectively in technologically saturated societies.

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<sup>63</sup> Collins, H. (2010). *Tacit and explicit knowledge*. University of Chicago Press.

<sup>64</sup> Wilson, M. (2002). Six views of embodied cognition. *Psychonomic Bulletin & Review*, 9(4), 625–636. <https://doi.org/10.3758/BF03196322>

<sup>65</sup> Tsai, Y.-S., Poquet, O., Gašević, D., Dawson, S., & Pardo, A. (2019). Complexity leadership in learning analytics: Drivers, challenges and opportunities. *British Journal of Educational Technology*, 50(6), 2839–2854. <https://doi.org/https://doi.org/10.1111/bjet.12846>

In practical terms, education should foster tacit knowledge by creating learning environments that enable students to learn through situated, embodied, and social experiences. This includes expanding hands-on activities such as laboratory work, design projects, crafts, and maker-based learning; strengthening apprenticeship-like models through mentoring, peer collaboration, and guided practice; and integrating problem-based and experiential pedagogies that require learners to experiment, improvise, and reflect. Because tacit knowledge develops through doing rather than through abstract explanation, schools and universities should deliberately balance digital instruction with rich opportunities for physical engagement, iterative creation, and real-world participation. These practices ensure that learners acquire the intuitive judgment, practical competence, and context sensitivity that explicit instruction alone cannot provide.

## Adaptability as a core educational outcome

Rapid technological change increasingly renders static skill sets obsolete. As tasks, tools, and roles evolve faster than formal qualifications, the capacity to adapt—cognitively, strategically, and emotionally—becomes a foundational educational outcome. Adaptability is not a vague “soft skill,” but a **KEY** capability that governs how effectively individuals can acquire, reorganize, and discard knowledge and behaviors over time.

Research shows that adaptability is teachable when learning environments are designed to engage uncertainty productively. This requires pedagogies that allow for struggle, revision, and exploration, rather than rewarding speed and correctness alone. The pedagogy of productive failure allows learners to struggle with complex problems before formal instruction, thereby enhancing conceptual understanding and transfer.<sup>66</sup> Cognitive flexibility training is a pedagogy of structured exposure to task switching and rule changes that improves executive function performance, particularly on near-transfer tasks.<sup>67</sup> In motor and cognitive learning, varied, non-repetitive practice improves retention and adaptability compared to repetitive drills.<sup>68</sup>

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<sup>66</sup> Kapur, M. (2008). Productive Failure. *Cognition and Instruction*, 26(3), 379–424. <https://doi.org/10.1080/07370000802212669>

<sup>67</sup> Diamond, A., & Ling, D. S. (2016). Conclusions about interventions, programs, and approaches for improving executive functions that appear justified and those that, despite much hype, do not. *Developmental Cognitive Neuroscience*, 18, 34–48. <https://doi.org/10.1016/j.dcn.2015.11.005>; Van Damme, D. & Fadel, C. (2025). *Executive Functions. Conceptual Framework and Relevance for Education*, Center for Curriculum Redesign. <https://curriculumredesign.org/wp-content/uploads/Executive-Functions-CCR.pdf>

<sup>68</sup> Wrisberg, C. A., & Liu, Z. (1991). The Effect of Contextual Variety on the Practice, Retention, and Transfer of an Applied Motor Skill. *Research Quarterly for Exercise and Sport*, 62(4), 406–412. <https://doi.org/10.1080/02701367.1991.10607541>; Pesce, C., et al. (2019). Variability of practice as an

It also requires assessment practices that value process, strategy, and reflection alongside outcomes. Traditional tests capture static knowledge more readily than adaptive capacity. Emerging approaches emphasize product-plus-process assessment, scoring strategies, revisions, and metacognitive reflection alongside outcomes. Scenario-based tasks with rule changes, coupled with self-explanations, offer promising avenues for capturing adaptability in action.

**Adaptability should not be treated as only a Layer 5 phenomenon** because it is not a “domain of competence” like epistemic judgement; it is a **dynamic property of learning and performance that operates across all layers**. Layer 5 *shapes* adaptability in complex environments, but it does not *contain* it.

1. Adaptability is a *process*, not a *content layer*: The 5 layers describe *types of competence* (foundational → procedural → conceptual → integrative → epistemic). Adaptability is different: it describes how competences change, reorganize, and remain functional under novelty. Thus, it behaves more like a cross-cutting capability (or a “meta-dynamic”) than a discrete tier.

Lower layers show adaptability too (and often earlier): Even very young learners adapt before they can do high-level epistemic reasoning:

2. Layer 1 (foundations): adapting attention, regulating effort, persisting through uncertainty. *Example*: sustaining focus when a task becomes harder; recovering after distraction.
3. Layer 2 (procedures): adapting routines and strategies. *Example*: switching methods when one algorithm fails; learning a new tool interface.

These are forms of adaptability that occur without Layer 5-level reflection.

4. If adaptability is located only at Layer 5, one risks making it “too cognitive”: Many of the most important adaptive behaviors are:
  - embodied (timing, coordination, perception),
  - emotional (tolerating ambiguity, recovering from failure),
  - behavioral (trying alternatives, revising plans).
  - Those live strongly in Layer 1 and Layer 2, not only in the epistemic layer.
    - Adaptability depends on *the quality of lower layers*: Layer 5 may supervise and direct adaptation, but adaptation is constrained by what exists underneath:
      - Weak foundational capacities (attention, memory) → brittle adaptation
      - Weak procedural fluency → overload and inability to pivot
      - Weak conceptual understanding → “trial-and-error” without transfer

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interface between motor and cognitive development. [International Journal of Sport and Exercise Psychology](#), 17(2), 133–152.

- Weak integrative sensemaking → adaptation remains narrow and local
- Thus, adaptability is an emergent property of the whole stack.

5. The best framing is: adaptability as *vertical mobility* across layers: In this model, adaptability is best understood as the ability to move between layers depending on the demands of the situation. For example, when AI produces an answer:
- One may need Layer 2 (execute),
  - Layer 3 (understand),
  - Layer 4 (transfer and integrate), and
  - Layer 5 (judge reliability and decide action).

Adaptability is the capacity to reconfigure the stack, not just “operate at the top.”

6. Layer 5 is still crucial – but as the *governor* of adaptation

Where Layer 5 *is special* is that it enables:

- recognizing when adaptation is needed (monitoring mismatch),
- diagnosing errors in tools or assumptions,
- calibrating confidence under uncertainty,
- choosing when to offload vs re-internalize,
- learning how to learn (meta-learning).
- Therefore Layer 5 does not “own” adaptability – it *steers it*.

***To summarize: Adaptability is not a fifth-layer competence; it is the capacity to update and reorganize competences across all layers—while Layer 5 provides the metacognitive and epistemic control that makes adaptation deliberate rather than accidental.***

At a system level, *adaptability reframes lifelong learning*: not as episodic retraining, but as sustained readiness to re-enter learning cycles across the life course. Education systems that fail to cultivate adaptability risk producing brittle learners—highly optimized for stable conditions that no longer exist.

In line with the broader historical analysis of technology-driven epistemic change developed in this paper, ***adaptability emerges as a modern analogue to earlier foundational skills such as literacy or numeracy: a general-purpose capacity that underpins all others.*** Designing education systems that cultivate it deliberately is therefore not optional but central to sustaining knowledge, autonomy, and resilience in the age of AI.

# Conclusions

## Is technology making humans “dumber”? Yes and No.

Whether humans are becoming “dumber” as technologies become “smarter” is less a question of raw neurological capacity than of how cognitive work is distributed between brains and tools. Technological innovation does not make humanity smarter or dumber—it redistributes cognition across humans, artifacts, institutions, and infrastructures. Current evidence does not indicate an apparent decline in underlying human cognitive capabilities; rather, it suggests a complex pattern of trade-offs, in which some skills weaken while others are augmented or offloaded to technological tools and devices.

First, large-scale intelligence data do not yet support a simple global decline. Classic research on the *Flynn effect* has shown substantial gains in IQ scores throughout the 20th century, likely attributable to improved nutrition, education, and environmental complexity.<sup>69</sup> More recent studies, however, have observed plateaus or slight declines in IQ scores in some high-income countries, a pattern sometimes referred to as the “reverse Flynn effect.”<sup>70</sup> These shifts appear to be driven by environmental and educational changes rather than genetics, and they vary by country and cohort, which complicates any claim that “technology is making us dumber.” Whether technological innovations have contributed to increases or declines in intelligence remains a matter of debate. Clark et al. have argued that the Flynn effect does not reflect genuine increases in general intelligence but rather an increasing aptitude for the cognitive processing required by modern life and measured by IQ tests.<sup>71</sup> Novel forms of interaction in our everyday life, enabled by technology, create a more stimulating environment for cognitive training, which may contribute to the Flynn effect.<sup>72</sup>

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<sup>69</sup> Flynn, J. R. (1987). Massive IQ gains in 14 nations: What IQ tests really measure. *Psychological Bulletin*, 101(2), 171–191. <https://doi.org/10.1037/0033-2909.101.2.171>

<sup>70</sup> Bratsberg, B., & Rogeberg, O. (2018). Flynn effect and its reversal are both environmentally caused. *Proceedings of the National Academy of Sciences*, 115(26), 6674–6678.

<https://doi.org/10.1073/pnas.1718793115>; Meisenberg, G., & Lynn, R. (2023). Ongoing trends of human intelligence. *Intelligence*, 96, 101708. <https://doi.org/10.1016/j.intell.2022.101708>

<sup>71</sup> Clark, C. M., Lawlor-Savage, L., & Goghari, V. M. (2016). The Flynn effect: A quantitative commentary on modernity and human intelligence. *Measurement: Interdisciplinary Research and Perspectives*, 14(2), 39–53. <https://doi.org/10.1080/15366367.2016.1156910>

<sup>72</sup> Pietschnig, J. (2016). The Flynn Effect: Technology May Be Part of It, But Is Most Certainly Not All of It. *Measurement: Interdisciplinary Research and Perspectives*, 14(2), 70–73. <https://doi.org/10.1080/15366367.2016.1171612>

Second, as discussed, digital technologies appear to reshape attention, memory, and problem-solving strategies. These findings support the notion that ubiquitous devices can impose a “cognitive load tax” on everyday cognition. At the same time, technology often functions as cognitive offloading, changing *where* information is stored and processed rather than reducing capacity. When people expect information to be available via digital tools, they remember the location of information better than its content. This does not necessarily mean people are less intelligent; instead, memory strategies shift from internal storage to external resources. Similarly, extended mind theorists argue that tools such as notebooks, calculators, and digital systems can become part of a broader cognitive system, thereby expanding what individuals can do. In sum, there is little evidence that humans are becoming “dumber” due to smarter technologies. Instead, digital environments are reshaping cognitive ecology: some traditional skills may decline, while capacities for information navigation, collaboration, and tool-mediated problem-solving may expand. **The key policy and educational challenge is not to resist intelligent technologies, but to design social and learning environments that cultivate deep attention, critical reasoning, and metacognitive control over when and how we offload cognition.**

## Balancing cognitive diminishment and enhancement

In Plato’s *Phaedrus*, Socrates recounts the myth of Theuth (the inventor of writing) and King Thamus, in which Thamus criticizes writing for harming memory. Writing will “produce forgetfulness in the souls of those who learn it, because they will not practice their memory.”<sup>73</sup> Socrates’ arguments are echoed in contemporary concerns about the effects of certain cognitive artefacts on onboard cognitive capabilities. Critics have pointed out that using calculators has reduced our ability to perform calculations in our head; navigation systems have reduced our ability to navigate; and having access to the internet results in storing less information in our brains. If cognitive technologies perform information storage or computational tasks for us, the brain systems that would otherwise perform those tasks tend to atrophy or lose capacity.<sup>74</sup> Our historical review has demonstrated that the risk of cognitive diminishment is not unique to our time, although the impact of artificial intelligence on cognitive functioning remains difficult to evaluate. Fasoli et al. call cognitive diminishment “the dark side” of the cognitive enhancement that technologies promise.<sup>75</sup>

<sup>73</sup> Plato, *Phaedrus*. 274c–275b (Stephanus pagination).

<sup>74</sup> Heersmink, R. (2024). Use of large language models might affect our cognitive skills. *Nature Human Behaviour*, 8(5), 805–806. <https://doi.org/10.1038/s41562-024-01859-y>

<sup>75</sup> Fasoli, M., Cassinadri, G., & Ienca, M. (2025). The Dark Side of Cognitive Enhancement: A Framework for the Technologically Induced Cognitive Diminishment. *Journal of Cognitive Enhancement*, 9(3), 346–359. <https://doi.org/10.1007/s41465-025-00331-7>

The concerns regarding cognitive diminishment are legitimate, as shown in this paper. However, technologies have also enhanced human cognitive functioning. Across history, technologies have consistently expanded human cognitive capacities by externalizing constraints and amplifying reach, precision, and coordination. Material technologies such as tools, fire, and infrastructure enhanced spatial reasoning and collective problem-solving by reshaping the environment itself. Symbolic technologies transformed cognition by enabling durable memory, abstraction, cumulative knowledge, and reasoning across time and distance. Mechanical technologies, including clocks, printing, and industrial machines, further enhanced cognition by standardizing time, scaling information dissemination, and supporting systematic measurement, calculation, and coordination. Digital technologies dramatically accelerated these gains, extending calculation, retrieval, navigation, and pattern recognition while enabling rapid access to vast stores of information and lowering barriers to complex cognitive tasks. Most recently, generative technologies augment human cognition by producing drafts, simulations, explanations, and synthetic representations that can scaffold reasoning, creativity, and exploration. Taken together, these technologies have not simply replaced human cognition but have expanded its functional reach—allowing individuals and societies to think at scales, speeds, and levels of complexity that would otherwise be unattainable.

**The challenge is to balance cognitive enhancement and cognitive diminishment. That is not primarily a technical problem, but a design, educational, and governance challenge.** History shows that every significant cognitive gain produced by technology comes with predictable trade-offs. The task, therefore, is not to maximize enhancement or minimize technology use, but to manage redistribution: deciding which cognitive functions should be delegated, which must remain human, and how education and institutions compensate for what everyday life no longer trains. The balance can be approached along four complementary levers.

**First, distinguish delegation from abandonment.** Technologies enhance cognition when they delegate routine, high-load, or error-prone operations (e.g., calculation, retrieval, drafting) while preserving human control over interpretation, judgment, and goal-setting. Cognitive diminishment occurs when delegation becomes abandonment—when individuals no longer develop the underlying conceptual, attentional, or experiential capacities needed to understand or supervise delegated outputs. Effective balance requires selective offloading: using tools to reduce load without eliminating opportunities for internal model-building, practice, and feedback.

**Second, protect non-delegable human capacities.** Foundational capacities such as attention regulation, memory formation, spatial and temporal orientation, embodied perception, and intuitive judgment do not automatically survive technological substitution. Because modern environments no longer reliably exercise these capacities, education and work must intentionally create conditions for their practice. This includes designing learning environments that support sustained attention, requiring learners to internalize key structures rather than merely retrieve them, and maintaining embodied, hands-on engagement when tacit knowledge is at issue.

**Third, shift educational emphasis upward.** As technologies increasingly automate procedural skills, the educational value of those skills lies less in execution and more in understanding. Cognitive enhancement is maximized when education reallocates effort toward conceptual and structural understanding—models, systems, causal reasoning—and toward epistemic meta-competence: evaluating sources, detecting errors, supervising automated systems, and knowing when not to trust outputs. This shift allows learners to benefit from technological power without becoming epistemically dependent on it.

**Fourth, cultivate adaptive and reflective use of technology.** Balance is dynamic, not static. As tools evolve, so do the risks of diminishment. Individuals and institutions therefore need adaptability and reflexivity: the capacity to monitor how technologies affect cognition, to recalibrate practices, and to re-internalize skills when needed. This includes teaching learners to reflect on their own reliance patterns, designing assessments that value process and judgment rather than speed alone, and governing technologies in ways that preserve transparency, contestability, and human accountability.

In short, the balance is achieved not by resisting technology, but by aligning delegation with human development—using technologies to extend cognition while ensuring that education, institutions, and design choices actively sustain the internal capacities that make such extension meaningful, reliable, and humane.

# Annex

The Annex presents twenty short case studies of notable past and current technological innovations, from fire to artificial intelligence. These case studies have also served as raw materials from which patterns have been distilled regarding the impact of technological innovations on human cognitive abilities. For each case study, the following questions guided the analysis:

- What was the significance of the technological advancement?
- What are the gains of the technology, more specifically for human knowledge and skills?
- What were the losses that the technology engendered?

## Fire

### Significance

The controlled use of fire was not merely a survival tool; it was an epistemic revolution that reshaped how early humans perceived, learned, and reasoned about the world. Before fire, human cognition operated within the constraints of daylight, raw foods, and constant vigilance against predators. With fire, these constraints loosened. Humans gained a portable source of heat, light, protection, and transformation—an unprecedented extension of agency. But fire also introduced new dependencies and reorganized the ecology of human thinking: it created shared spaces for storytelling and teaching, enabled new forms of causal inference, and encouraged temporal planning beyond immediate horizons. Fire changed what humans needed to know and how they came to know it.<sup>76</sup>

### Gains

- *A new platform for social learning and cultural transmission:* The hearth became humanity's first learning institution.<sup>77</sup> Gathered around flames, communities shared stories, norms, and techniques. Fire extended waking hours into the night, enabling reflective dialogue, instruction, and imaginative narration. These practices

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<sup>76</sup> Gowlett, J. A. J. (2016). The discovery of fire by humans: a long and convoluted process. *Philosophical Transactions of the Royal Society B*, 371, 20150164. <https://doi.org/10.1098/rstb.2015.0164>

<sup>77</sup> Lombard, M., and Gärdenfors, P. (2023). Minds on fire: cognitive aspects of early firemaking and the possible inventors of firemaking kits. *Cambridge Archaeological Journal*, 33(3), pp. 499-519. <https://doi.org/10.1017/S0959774322000439>

consolidated cultural memory and supported more structured, intergenerational transmission of knowledge than daylight-bound foraging allowed.

- *Amplified capacity for causal and transformative reasoning:* Fire enabled humans to witness matter changing: raw to cooked, clay to ceramic, ore to metal. These transformations nurtured early intuitions about cause, process, and material properties, forming the cognitive roots of later crafts and sciences. Fire demanded foresight—anticipating fuel needs, protecting embers, and rationing wood—thereby strengthening executive functions such as planning, inhibition, and working memory.<sup>78</sup>
- *Biological and sensory enhancements supporting cognition:* Cooking increased caloric efficiency and nutrient absorption, supporting brain expansion. Artificial light improved safety and freed humans from strict circadian limits, altering time perception and enabling new forms of attention, reflection, and shared imagination. Fire also sharpened sensory learning by drawing collective focus around a single luminous point.
- *Environmental and technological learning loops:* Controlled burning reshaped landscapes long before agriculture. Humans learned to identify burn patterns, manage vegetation, and understand seasonal cues. This produced embedded ecological knowledge and experimentation with environmental modification—early forms of applied science.

## Losses

- *Decline of pre-fire ecological and survival competencies:* As reliance on cooked food grew, skills for processing raw diets faded. Physiological cold tolerance diminished. Night vision, predator awareness, and adaptive mobility weakened when fire provided safety and illumination. Fire expanded survival possibilities but narrowed the diversity of competencies people needed.
- *Emergence of technological dependence and fragility:* Control of fire created a paradox: an innovation that made life safer also increased vulnerability. Losing fire—through weather, migrations, or inexperience—could be catastrophic. Groups without reliable fire-making skills risked sudden epistemic paralysis, lacking both the tool and the knowledge to thrive without it.
- *Ecological simplification and loss of environmental attunement:* Frequent burning altered ecosystems, reducing biodiversity and obscuring knowledge of pre-fire flora and fauna. Familiarity with natural cues—migratory patterns, forage diversity, microclimates—declined as human environments became more fire-managed and less wild.

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<sup>78</sup> Twomey, T. (2013). The cognitive implications of controlled fire use by early humans. *Cambridge Archaeological Journal*, 23(1), pp. 113-128. <https://doi.org/10.1017/S0959774313000085>

- *Concentration of knowledge and authority:* Expertise in tending and transporting fire could become a source of power. Ritual specialists, elders, or designated fire-keepers gained status, while others became dependent on their competence. This marked one of the earliest shifts from distributed to asymmetric knowledge.

Fire’s epistemic legacy is double: it expanded human imagination and control while narrowing earlier forms of environmental mastery. It marks the first moment when humans co-evolved with a technology that fundamentally altered cognition, culture, and the distribution of knowledge.

## Agriculture

### Significance

The Neolithic Revolution, occurring approximately 10,000-5,000 years ago, represented one of humanity’s most significant transitions from hunting-gathering to agricultural food production.<sup>79</sup> This transformation fundamentally altered human perception and cognition by promoting attentiveness to previously unnoticed aspects of reality, thereby expanding the horizons of perception and thinking.<sup>80</sup> Farming was not a single invention but the convergence of domestication, irrigation, storage, and settlement.<sup>81</sup> These practices required new forms of prediction, measurement, and coordination, bringing forth a cognitive style centered on abstraction, planning, and control. Agriculture required that people observe cycles, quantify yields, classify natural phenomena, and create durable records. As a result, it replaced the fluid, tacit, wide-ranging knowledge of foragers with structured systems of agronomic, administrative, and calendrical reasoning.

According to recent archaeological evidence, this transition didn’t happen smoothly or peacefully. The transition led to widespread violence.<sup>82</sup> According to J.C. Scott, the agricultural revolution was not a step towards human progress but rather one of the

<sup>79</sup> Martin-Merino, M. (2021). The Neolithic Revolution : agriculture, sedentary lifestyle and its consequences. *Cambridge Open Engage*. <https://doi.org/10.33774/coe-2021-2589h>

<sup>80</sup> Herva, V. P., Nordqvist, K., Lahelma, A., and Ikäheimo, J. (2014). Cultivation of Perception and the Emergence of the Neolithic World. *Norwegian Archaeological Review*, 47(2), 141–160. <https://doi.org/10.1080/00293652.2014.950600>

<sup>81</sup> Bogaard, A. (2005). ‘Garden agriculture’ and the nature of early farming in Europe and the Near East. *World Archaeology*, 37(2), pp. 177–196. <https://doi.org/10.1080/00438240500094572>

<sup>82</sup> Curry, A. (2025). A headless mystery. *Science*. 20 November 2025. <https://www.science.org/doi/epdf/10.1126/science.aed9987?s=09>

worst events in human history. Early foraging societies were often healthier, more diverse in their diets, and less labor-intensive than the earliest agricultural communities. It also created conditions for state control, inequality, disease, and coercive labor.<sup>83</sup>

## Gains

- *Temporal literacy and future-oriented cognition:* Agriculture forced humans to attend to long cycles: seasons, rainfall patterns, germination times. Calendars, rituals, and early astronomy emerged to track these rhythms. This temporal orientation cultivated predictive reasoning—anticipating yields, planning irrigation, forecasting shortages.
- *Emergence of agronomic and ecological expertise:* Farmers learned soil composition, seed selection, water management, crop rotation, and pest control. These practices generated abstract ecological categories—“field,” “weed,” “pest”—that enabled systematic intervention and the production of generalizable knowledge.
- *Quantification, codification, and proto-writing:* Surplus production required counting, measuring, storing, and taxing. This administrative burden stimulated the development of numerical systems, inventories, and bookkeeping. In many regions, writing originated as a means of tracking agricultural goods and gradually became a foundational cognitive technology.
- *Specialization and distributed knowledge systems:* Sedentary life enabled professional diversification: scribes, millers, potters, surveyors. Knowledge became institutionally supported—preserved in granaries, tablets, and early bureaucracies.

## Losses

- *Erosion of forager knowledge and mobility skills:* Where foragers mastered hundreds of species and microhabitats, agriculturalists focused on a narrow set of domesticated plants and animals. Knowledge of wild foods, seasonal migrations, and ecosystem variability diminished sharply.
- *Reduced adaptive flexibility:* Farming locked communities into place—both geographically and cognitively. Dependence on fixed plots and routine schedules decreased responsiveness to ecological change, increasing vulnerability to drought, pests, and crop failure.
- *Centralization of expertise and rising inequality:* Administrative literacy and land measurement became specialized skills, concentrated in temples or state offices.

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<sup>83</sup> Scott, J.C. (2017). *Against the grain: A deep history of the earliest states*. Yale University Press.

This created epistemic hierarchies: some controlled the calendars, records, and redistribution; others supplied labor.

- *Ecological simplification and systemic fragility*: Monocultures increased yield but reduced biodiversity and resilience. Cognitive focus narrowed on standardized categories, obscuring ecological interdependencies that had guided forager knowledge systems.

Agriculture marks the transition from fluid, situational knowledge to structured, institutionalized cognition. It expanded predictive reasoning and enabled complex societies, but at the cost of ecological attunement, mobility wisdom, and egalitarian knowledge.

## Writing

### Significance

The invention of writing—first in Near Eastern token-and-tablet systems and later in complete scripts—externalized memory. Clay, papyrus, ink, stylus, and the patterned marks themselves formed a system that could stabilize information across time and space.<sup>84</sup> At its core, writing transformed ephemeral speech and memory into enduring, inspectable objects. By materializing language, it enabled information to be stabilized across distance and time, creating a substrate for administration, law, literature, and science. The later innovation of the alphabet sharpened this revolution. By reducing the graphic repertoire to a small set of symbols corresponding to phonemes, alphabets lowered the threshold of literacy and encouraged new kinds of analytic reflection on language itself.<sup>85</sup>

- *Materialization of memory*: Spoken words could now “outlast” the speaker, stored in durable materials like clay or papyrus. Records outlived individuals, enabling societies to coordinate across generations and to retrace causality across generations.
- *Standardization of communication*: Writing allowed a degree of precision impossible in oral performance, reducing ambiguity and variation.
- *Spatial extension of communication*: Writing allowed information to travel vast distances with greater fidelity than oral messengers.

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<sup>84</sup> Schmandt-Besserat, D. (1996). *How writing came about*. University of Texas Press; Goody, J. (1986). *The logic of writing and the organization of society*. Cambridge University Press.

<sup>85</sup> Drucker, J. (2024), Inventing the alphabet: the technologies of knowledge production. *History and Theory*, 63: pp. 319-341. <https://doi.org/10.1111/hith.12356>; Eviatar, Z. & Huettig, F. (2021). The literate mind. *Journal of Cultural Cognitive Science*. 5, pp. 81–84. <https://doi.org/10.1007/s41809-021-00086-5>

- *Speed in transmission*: Information traveled faster, at horseback speed, without the author needing to travel.
- *Acceleration of abstraction*: Once speech was objectified, it became possible to analyze, reorganize, and manipulate language itself as a structure.
- *Shift in learning curves*: Alphabets, by drastically reducing the number of signs, made reading and writing more teachable, allowing literacy to spread beyond narrow scribal elites.
- *Platform for new media forms*: From poetry and epics to legal codes and philosophical treatises, writing enabled genres that depend on precision, length, or cumulative argumentation.

## Gains

- *Durable knowledge*: Records no longer disappeared with a storyteller's death; knowledge could accumulate across generations.
- *Precision and clarity*: Written laws, measurements, and instructions reduced the ambiguity of oral transmission.
- *New ways of thinking*: Once language was visible, people could analyze it. Grammar, logic, rhetoric, and philosophical argument developed from written traditions.
- *Cumulative learning*: Libraries and archives became humanity's first knowledge infrastructures.

## Losses<sup>86</sup>

- *Oral virtuosity*: Cultures that once relied on prodigious memory shifted toward external storage. Internal memorization skills declined.
- *Context and nuance*: Written sentences lack the tone, gesture, and social cues that give meaning to spoken words.
- *Access barriers*: For centuries, literacy was controlled by elites, concentrating knowledge and power.
- *Marginalization of tacit knowledge*: Erosion of unwritten knowledge; those who had no access to written knowledge, only had the tacit knowledge to rely on.
- *Rigid categories*: What is written down often becomes fixed, leaving less room for fluidity and interpretation.

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<sup>86</sup> Olson, D. R. (1994). *The world on paper: The conceptual and cognitive implications of writing and reading*. Cambridge University Press. Ong, W. J. (1982). *Orality and literacy: The technologizing of the word*. Methuen.

# Construction

## Significance

Early construction—irrigation systems, roads, bridges, drains, and city grids—represented a shift from adapting to landscapes toward reorganizing them.<sup>87</sup> These works demanded systematic measurement, durable materials, and coordinated labor. As construction practices evolved, they generated new ways of conceptualizing space, scale, and permanence. Engineering became not just a set of techniques but a mode of reasoning that emphasized clarity, predictability, and repeatability.<sup>88</sup>

## Gains

- *Embedding geometric reasoning in practical life:* Surveying tools taught practitioners to handle angles, alignments, and gradients. These measurable relations supported more exact planning and helped standardize construction practices.<sup>89</sup>
- *Formalization of procedures and documentation:* Handbooks and diagrams codified processes—from leveling a road to calculating water flow—making expertise transferable across projects and generations.
- *Skills for coordinating complex work:* Large infrastructures required scheduling, division of labor, and inspection routines. These competencies reinforced systematic thinking and improved the reliability of shared utilities.
- *New territorial knowledge:* Mapping and cadastral surveys encouraged viewing land in standardized units rather than through local custom. This supported taxation, zoning, and administrative control.

## Losses

- *Decline of local architectural traditions:* As standardized designs spread, regionally adapted building knowledge—responsive to local materials or climate—lost value and visibility.

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<sup>87</sup> Oleson, J.P. (ed.) (2009). *The Oxford Handbook of Engineering and Technology in the Classical World*, Oxford Handbooks. <https://doi.org/10.1093/oxfordhb/9780199734856.001.0001>; Pacey, A. and Bray, F. (2021). *Technology in World Civilization: A Thousand-Year History*. The MIT Press. <https://doi.org/10.7551/mitpress/11467.001.0001>

<sup>88</sup> Mokyr, J. (2002). *The Gifts of Athena: Historical Origins of the Knowledge Economy*. Princeton University Press.

<sup>89</sup> Lewis, M. J. T. (2001). *Surveying Instruments of Greece and Rome*. Cambridge University Press.

- *Narrowing of environmental perception:* Seeing land as a grid or a channel simplified ecological understanding. The focus on straight lines and predictable flows obscured seasonal variability and subtle ecological interactions.
- *Growing separation between experts and users:* Engineers, surveyors, and administrators increasingly defined what counted as correct or safe. Ordinary inhabitants had less interpretive agency over spaces they lived in.
- *Entrenchment of infrastructural dependency:* Once canals, roads, or drainage systems were established, communities relied on them. Alternative practices—like shifting fields or seasonal mobility—became harder to sustain.

Construction reorganized cognition around measurement and system maintenance. It strengthened societies' capacity for large-scale coordination but marginalized diverse spatial knowledges and deepened dependence on designed environments.

## Mechanical timekeeping

### Significance

Mechanical clocks redefined how people experienced and interpreted time. Earlier societies relied on daylight, bells, or seasonal cues, all of which tied time to natural rhythms. With escapement mechanisms and pendulums came uniform hours and portable precision. Time became something that could be compared across places, recorded in detail, and used to structure work and mobility. This shift transformed not only daily routines but also scientific practice and collective coordination.<sup>90</sup>

### Gains

- *Precision enabling new forms of inquiry:* Equal hours made it possible to track celestial movements, conduct synchronized experiments, and calculate longitude at sea. Scientific observation became more reliable because events could be timed accurately.
- *Shared schedules and coordinated action:* Urban clocks synchronized communal life. Later, railways and telegraphy required standardized time zones, teaching people to read timetables and align their activities with distant centers.
- *Internalization of punctuality and duration:* Clocks encouraged people to think in discrete intervals. Managing one's day required estimating duration, sequencing

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<sup>90</sup> Dohrn-van Rossum, G. (2015). 'Time', in: H. Scott (ed.). *The Oxford Handbook of Early Modern European History, 1350-1750: Volume I: Peoples and Place*. Oxford Academic, pp. 145-164. <https://doi.org/10.1093/oxfordhb/9780199597253.013.5>; Landes, D.S. (1983). *Revolution in Time: Clocks and the Making of the Modern World*. Harvard University Press.

tasks, and anticipating deadlines—competencies that underlie modern education and labor systems.

- *Expansion of administrative and economic organization:* Factories, schools, and offices coordinated people by fixed hours. This fostered skills in planning, scheduling, and temporal comparison across activities.

## Losses

- *Decline of natural temporal awareness:* Fluctuations in daylight or seasonal rhythms became less central to decision-making. Knowledge of cyclical time and task-based pacing weakened.
- *External control over personal rhythms:* Time schedules could enforce rigid routines and discipline, reducing autonomy and prioritizing efficiency over individual or communal needs.<sup>91</sup>
- *Homogenization of temporal diversity:* Regional time customs gave way to standardized norms. Plural understandings of time—ritual, seasonal, communal—lost prominence.
- *Overemphasis on quantification:* Viewing time as a resource to manage encouraged habits of optimization that can obscure qualitative experiences—rest, interruption, creativity—that resist measurement.

Mechanical timekeeping strengthened coordination and scientific precision but narrowed temporal imagination and weakened forms of knowledge rooted in natural rhythms and embodied experience.

## Perspective

### Significance

The development of linear perspective in the Renaissance transformed not only artistic practice but also the structure of visual knowledge.<sup>92</sup> Prior to perspective, images did not aspire to replicate the viewer's optical experience; they served symbolic, narrative, or devotional functions. Perspective introduced the idea that space could be represented according to geometric rules grounded in a single observer's point of view. This

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<sup>91</sup> Thompson, E. P. (1967). Time, work-discipline and industrial capitalism. *Past and Present*, 38, pp. 56–97. <https://doi.org/10.1093/past/38.1.56>; Glennie, P. and Thrift, N. (2009). *Shaping the Day: A History of Timekeeping in England and Wales 1300–1800*. Oxford University Press.

<sup>92</sup> De Mey, M. (1992). Linear Perspective: Intellectual or Rhetoric Innovation? Intellectual or Rhetoric Innovation? *Cultural Dynamics*, 5(1), 1-24. <https://doi.org/10.1177/092137409200500101>

technique encouraged a new understanding of vision as measurable and governed by principles that could be learned and reproduced. Perspective thus bridged artistic practice and scientific inquiry, reshaping Western conceptions of objectivity, distance, and the observer's role.<sup>93</sup>

## Gains

- *A systematic method for representing spatial depth:* By using vanishing points, horizon lines, and proportional scaling, perspective offered artists and architects a reliable framework for conveying three-dimensional relationships. This fostered precise visual reasoning and encouraged analytical thinking about form and space.
- *A new understanding of vision as rule-governed:* Perspective implied that seeing was not merely subjective but followed discoverable principles of projection. This insight supported early optics and helped connect artistic observation with mathematical description.
- *Enhanced observational skills:* Training in perspective required careful attention to angles, surfaces, and relative positions. Artists developed sharper abilities to perceive spatial subtleties, influencing fields such as anatomy, cartography, and engineering.
- *Transfer of visual literacy to technical disciplines:* Architects and planners adopted perspectival drawing as a tool for presenting designs and explaining structures. Navigators, surveyors, and mapmakers similarly benefited from more coherent spatial representation.

## Losses

- *Narrowing of visual conventions:* Perspective's success elevated one spatial logic above others. Symbolic, multi-view, and culturally diverse representational systems were marginalized, reducing the repertoire of visual expression.
- *Reinforcement of the isolated observer:* Perspective centered all representation on a fixed viewpoint, encouraging a cognitive model in which the viewer stands outside the world, observing from a distance. This could obscure relational, embodied, or communal ways of seeing.
- *Overconfidence in visual realism:* Images constructed through perspective gained an aura of accuracy and neutrality. Yet perspective is itself a convention; its

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<sup>93</sup> Crary, J. (1990). *Techniques of the observer: On vision and modernity in the nineteenth century*. MIT Press.

authority sometimes masked the choices, omissions, and distortions inherent in representation.

- *Loss of interpretive diversity:* As perspective became dominant in art and design education, the capacity to interpret or value non-perspectival systems diminished, narrowing visual imagination.

Perspective did more than improve drawing technique: it reorganized how societies understood space, observation, and representation. It helped articulate a worldview grounded in measurable relations while obscuring alternative visual epistemologies.

## Printing

### Significance

The printing press revolutionized the production and circulation of texts. Before the advent of printing, manuscripts were scarce, costly, and prone to copying errors. Printing enabled the rapid production of identical copies and their widespread distribution. This shift reshaped how people acquired information, how institutions preserved it, and how public debate unfolded. This ushered in a mechanization of communication, comparable in its impact to the later digital revolution.<sup>94</sup> Print culture encouraged habits of close reading, comparison across texts, and engagement with standardized references. It created new expectations about accuracy, permanence, and accessibility. It transformed the institutions of knowledge, such as universities.<sup>95</sup>

### Gains

- *Expansion of access to written knowledge:* Books became affordable and increasingly available to broader populations. Literate readers could consult multiple sources, cross-check claims, and accumulate personal libraries.
- *Stabilization of texts and ideas:* Printing ensured that editions remained consistent, enabling reliable transmission of scientific observations, legal codes, and educational materials. This stability supported cumulative learning.

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<sup>94</sup> Eisenstein, E. L. (1980). *The printing press as an agent of change*. Cambridge University Press; Febvre, L., and Martin, H. J. (1976). *The coming of the book: The impact of printing, 1450–1800*. Verso; Harnad, S. (1991). Post-Gutenberg Galaxy: The Fourth Revolution in the Means of Production of Knowledge. *Public-Access Computer Systems Review*. 2 (1): 39 – 53. <https://hdl.handle.net/10657/5147>

<sup>95</sup> Moodie, G. (2014). Gutenberg's effects on universities. *History of Education*, 43(4), 450–467. <https://doi.org/10.1080/0046760X.2014.930186>

- *New reading competencies*: Print fostered silent, sustained reading and the ability to navigate indexes, footnotes, and tables of contents. These practices promoted analytical habits and facilitated deeper engagement with complex arguments.
- *Growth of public discourse and collective critique*: Pamphlets, newspapers, and religious tracts enabled widespread discussion. Readers developed skills in evaluating competing viewpoints, and societies experimented with new forms of public reasoning.

## Losses

- *Decline of manuscript and oral traditions*: The authority of printed texts reduced the value of local storytelling, recitation, and scribal practices. Communities lost skills in memorization and in producing texts adapted to local contexts.
- *Standardization at the expense of diversity*: Printers favored widely marketable works, reinforcing dominant languages and suppressing minority literacies. Regional styles, vocabularies, and interpretive traditions weakened.
- *Information overload and uneven comprehension*: As printed materials multiplied, readers faced challenges of selection and evaluation. Not all readers had equal competence in critical reading, deepening literacy divides.
- *New forms of authority and gatekeeping*: Control over presses and distribution networks created centralized powers. What became “known” or publicly debatable increasingly depended on printers, editors, and censors.

Printing transformed knowledge by making it iterable and widely shared. It strengthened habits of critical reading and comparison while narrowing the range of expression and consolidating cultural authority.

## Mechanization

### Significance

The Industrial Revolution (c. 1750–1850) was not a single invention but a cluster of interconnected changes in energy, machinery, organization, and communication. Together, these constituted a shift from dispersed, household-based production to the centralized, power-driven factory—a “technological system” that reordered both production and thought.<sup>96</sup> Where artisanal production relied on tacit knowledge and flexible judgment, mechanized factories emphasized uniformity, speed, and division of

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<sup>96</sup> Landes, D. S. (1969). *The unbound Prometheus: Technological change and industrial development in Western Europe from 1750 to the present*. Cambridge University Press; Mokyr, J. (2002); Mokyr, J. (2009). *The enlightened economy: An economic history of Britain 1700–1850*. Yale University Press.

labor. This shift profoundly altered the skills required for work and reshaped how knowledge was produced, stored, and transmitted. Machines reorganized cognitive attention, turning workers into monitors of processes rather than creators of objects. The Industrial Revolution was also epistemic, building on and amplifying the seventeenth-century scientific revolution, which sought to apply natural philosophy to solve technological problems and promote economic growth, and the eighteenth-century Enlightenment, with its preference for rational thought and “useful knowledge.”<sup>97</sup>

## Gains

- *Reliance on formalized, transferable procedures:* Mechanization required written instructions, standardized measurements, and explicitly defined tasks. This promoted procedural literacy and made technical knowledge easier to communicate and replicate.
- *Emergence of engineering as a systematic discipline:* Designing machines demanded mathematical modeling, experimentation, and documentation. These practices expanded scientific thinking and tied knowledge to measurable performance.
- *Increased productivity enabling broader access to goods:* Mass production reduced costs and allowed more people to acquire tools, clothing, books, and household items, indirectly supporting education and literacy.
- *New supervisory and analytical skills:* As workers shifted from crafting to overseeing machines, competencies like troubleshooting, coordination, and process optimization became essential.

## Losses

- *Erosion of tacit craft knowledge:* Machines replaced many artisanal techniques—judging materials by feel, adapting designs spontaneously, or integrating aesthetic and functional decisions. Communities lost intergenerational craft lineages.
- *Disconnection from the full production process:* Division of labor fragmented understanding. Workers often knew only a narrow step, weakening holistic comprehension of tools, materials, and design.
- *Temporal and psychological strain:* Factory schedules forced workers into rigid temporal structures. Skills in pacing work according to task demands or bodily rhythms diminished.

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<sup>97</sup> Mokyr, J. (2005). The Intellectual Origins of Modern Economic Growth. *The Journal of Economic History*, 65(2), 285–351. <https://doi.org/10.1017/S0022050705000112>; Berg, M. (2007). The genesis of 'useful knowledge'. *History of Science*, 45/2, pp. 123-133. <https://doi.org/10.1177/007327530704500201>

- *Monoculture of efficiency:* Mechanization encouraged viewing success in quantitative terms—output, speed, uniformity—reducing space for improvisation, experimentation, and qualitative judgment.

Mechanization shifted knowledge toward explicit, rule-bound systems and away from embodied, situated expertise. It enriched engineering and administrative literacies while eroding integrated, craft-based ways of knowing.

## Chemistry

### Significance

Modern chemistry emerged from alchemy, metallurgy, and pharmacy, transforming disparate craft traditions into a systematic science of substances. By classifying elements, identifying reactions, and quantifying transformations, chemistry created a new epistemic framework for understanding matter. It equipped societies to manipulate materials at an unprecedented scale, enabling innovations from medicine to agriculture to industrial production. This transformation was characterized by the professionalization and institutionalization of scientific practice, replacing amateur generalists with professional specialists.<sup>98</sup>

### Gains

- *A unified conceptual system for material behavior:* The periodic table,<sup>99</sup> reaction equations, and atomic theory allowed chemists to predict interactions and design new substances. These abstract models translated complex phenomena into coherent, teachable principles.
- *Enhanced laboratory competencies:* Chemistry cultivated precision in measurement, observation, and documentation. Students and practitioners learned to design experiments, control variables, and interpret results through replicable methods.<sup>100</sup>
- *Expansion of applied knowledge:* Chemical insight enabled fertilizers, pharmaceuticals, plastics, and energy sources. These applications extended

<sup>98</sup> Nye, M.J. (1996). *Before Big Science: The Pursuit of Modern Chemistry and Physics, 1800-1940*. Harvard University Press; Bensaude-Vincent, B. & Stengers, I. (1996). *A history of chemistry*. Harvard University Press. Brock, W. H. (2000). *The chemical tree: A history of chemistry*. W. W. Norton; Ihde, A. J. (1964). *The development of modern chemistry*. Harper & Row.

<sup>99</sup> Scerri, E. (2007). *The periodic table: Its story and its significance* (2nd ed.). Oxford University Press.

<sup>100</sup> Jackson, C.M. (2011). Chemistry as the defining science: discipline and training in nineteenth-century chemical laboratories. *Endeavour*, 35(2–3), 55–62. <https://doi.org/10.1016/J.ENDEAVOUR.2011.05.003>; Cunningham, A., & Williams, P. (Eds.). (1992). *The laboratory revolution in medicine*. Cambridge University Press.

scientific reasoning into agriculture, medicine, public hygiene,<sup>101</sup> and industry, reshaping societal expectations of problem-solving.<sup>102</sup>

- *Strengthening of interdisciplinary thinking:* As chemistry connected physics, biology, and engineering, it encouraged integrative approaches to understanding natural and manufactured systems.

## Losses

- *Displacement of traditional material knowledge:* Local expertise in dyes, fermentation, metallurgy, or healing practices was often overshadowed by laboratory-based science. This resulted in the loss of nuanced, context-specific methods.
- *Environmental and sensory distancing:* Chemical processes moved from open, observable settings into enclosed laboratories. People became less attuned to natural indicators—smells, colors, textures—that once guided material understanding.
- *Growing abstraction and opacity:* While chemical models unified understanding, they also distanced learners from the tangible qualities of matter. Atomic and molecular explanations can feel remote from everyday experience.
- *Risks and dependencies:* Synthetic chemicals created new hazards—from pollution to toxicity—that require specialist knowledge to detect and manage. Public understanding often lags behind chemical innovation.

Chemistry reorganized humanity's relationship to matter by replacing experiential, place-based knowledge with systematic, experimental reasoning. It deepened predictive and manipulative power while introducing new ecological and epistemic vulnerabilities.

## Electricity

### Significance

Electricity transformed human life by providing a universal, controllable source of power and illumination. While its material effects—light, heat, motion—are widely acknowledged, its epistemic consequences are equally far-reaching. Electricity reorganized how people accessed information, structured work, and interacted with their environments. It enabled continuous activity detached from natural cycles. It

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<sup>101</sup> Hamlin, C. (2007). The City as a Chemical System? The Chemist as Urban Environmental Professional in France and Britain, 1780–1880. *Journal of Urban History*, 33(5), 702-728. <https://doi.org/10.1177/0096144207301416>

<sup>102</sup> Shapin, S. (2008). *The scientific life: A moral history of a late modern vocation*. University of Chicago Press.

created new forms of expertise in generation, distribution, and safety. Electricity became an invisible infrastructure for modern knowledge, shaping assumptions about what can be done, when it can be done, and how environments ought to behave.<sup>103</sup>

## Gains

- *Expansion of productive and learning time:* Electric light decoupled human activity from daylight, allowing study, craft, and communication to occur at any hour. This facilitated extended reading, scientific experimentation, and continuous industrial processes.
- *Standardization of power and predictable performance:* Electricity provided stable, uniform power for devices, enabling precise machines, instruments, and laboratory tools to become commonplace. New competencies developed around calibrated measurement and controlled experimentation.<sup>104</sup>
- *Growth of electrically mediated communication and knowledge networks:* Telegraphs, telephones, and radio created immediate information flows. Users acquired skills in remote coordination and learned to navigate increasingly complex infrastructures.
- *Emergence of new technical professions:* Electricians, engineers, and technicians cultivated specialized knowledge of circuits, insulation, motors, and grids. Educational institutions expanded to train expertise in electrical theory and safety.

## Losses

- *Decline of pre-electrical domestic and craft skills:* Oil lamps, hand tools, and manual heating methods receded. Knowledge of fire management, hand-powered devices, and daylight-use planning became less central.
- *Growing dependence on complex, opaque infrastructure:* Electricity is easily taken for granted until it fails. Users often lack understanding of generation, grids, and safety, rendering them dependent on specialists.
- *Environmental distancing and energy invisibility:* Electricity abstracts energy from its sources. People no longer see fuel or the labor behind it, weakening environmental awareness and reducing competencies for energy management.<sup>105</sup>

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<sup>103</sup> Marvin, C. (1988). *When old technologies were new: Thinking about electric communication in the late nineteenth century*. Oxford University Press; Nye, D. E. (1990). *Electrifying America: Social meanings of a new technology, 1880–1940*. MIT Press.

<sup>104</sup> Yates, J., & Murphy, C. N. (2019). *Engineering rules: Global standard setting since 1880*. Johns Hopkins University Press.

<sup>105</sup> Marvin, C. (1988). *When old technologies were new: Thinking about electric communication in the late nineteenth century*. Oxford University Press.

- *Vulnerability to systemic breakdown:* Blackouts reveal how thoroughly modern life relies on electricity. Many essential competencies—navigation, heating, communication—depend on uninterrupted power.

Electricity created unprecedented opportunities for learning, coordination, and technical precision, but detached daily life from natural rhythms and fostered dependence on vast, unseen infrastructures.

## Transportation

### Significance

At the turn of the 20th century, two intertwined innovations reshaped everyday life: privately owned, motorized road vehicles and rapidly scaling mass-transit networks (streetcars, subways, motor buses). Together, they reorganized how distance, time, and co-presence were experienced and coordinated, a phenomenon that social scientists later came to call a “mobilities” revolution.<sup>106</sup> Modern transportation—railways, automobiles, aviation—profoundly altered how people perceive distance, place, and movement. Speed and mass mobility compressed geographic space and reshaped economic, social, and cognitive landscapes. Transportation technologies changed not only how people travel, but also what they must understand to navigate the world. Skills related to orientation and local route knowledge gave way to system-based literacies involving schedules, maps, and later machine interfaces.

### Gains

- *Expansion of geographical horizons:* Trains and planes allowed people to traverse large distances quickly, fostering familiarity with broader regions and cultures. This expanded spatial imagination and encouraged comparative thinking.
- *New competencies in system navigation:* Timetables, ticketing, standardized routes, and map-reading required new literacies. Users learned to coordinate with large networks and interpret abstract spatial representations.
- *Increased access to knowledge and services:* Mass transit and personal autos enlarged labor and social catchment areas, creating new forms of urban/regional knowledge exchange (universities, cultural venues, industrial clusters).<sup>107</sup>

<sup>106</sup> Urry, J. (2007). *Mobilities*. Polity; Sheller, M. (2017). From spatial turn to mobilities turn. *Current Sociology*, 65(4), 623-639. <https://doi.org/10.1177/0011392117697463>

<sup>107</sup> Young, J. (2015). Infrastructure: Mass Transit in 19th- and 20th-Century Urban America. *Oxford Research Encyclopedia of American History*. <https://oxfordre.com/americanhistory/view/10.1093/acrefore/9780199329175.001.0001/acrefore-9780199329175-e-28>

- *Growth of engineering and logistical expertise:* Transportation infrastructures demanded specialized knowledge—track design, traffic control, aerodynamics, safety protocols—leading to advanced training and professional standards.

## Losses

- *Decline of local navigation and embodied orientation:* Walking paths, seasonal trails, and orally transmitted route knowledge lost relevance. People became less attuned to natural landmarks, weather patterns, and bodily cues associated with travel.
- *Reduced independence from infrastructure:* Mobility increasingly required maintained roads, fuel systems, and regulatory regimes. When these systems falter, alternative travel skills are often absent.
- *Homogenization of spatial experience:* Standardized transportation corridors bypass diverse terrains and communities. Travelers encounter curated routes rather than rich landscape variation, narrowing experiential knowledge.
- *Environmental and cognitive distancing:* High-speed transport encourages an abstract sense of space detached from ecology. Distances feel smaller, but understanding of the places traversed can diminish. Faster, farther routine trips recalibrated people’s mental maps and notions of proximity—what theorists later call *time-space compression*.<sup>108</sup>

Transportation technologies broadened human movement while narrowing earlier place-based knowledge. They cultivated new literacies for navigating complex systems but displaced intimate spatial awareness and endurance-based competencies.

## Refrigeration

### Significance

Refrigeration and air conditioning reconfigured the relationship between humans and their environments. By controlling temperature and preserving food, these technologies reshaped daily routines, diets, and expectations of comfort.<sup>109</sup> They also transformed how people understand perishability, seasonality, and climatic variation. Refrigeration and climate control have significantly altered competencies in food storage, environmental adaptation, and sensory judgment.

<sup>108</sup> Dodgshon, R. A. (1999). Human Geography at the End of Time? Some Thoughts on the Notion of Time-Space Compression. *Environment and Planning D: Society and Space*, 17(5), 607-620. <https://doi.org/10.1068/d170607>

<sup>109</sup> Rees, J. (2013). *Refrigeration Nation: A history of ice, appliances, and enterprise in America*. Johns Hopkins University Press.

## Gains

- *Reliable preservation and expanded diets:* Refrigeration extended the lifespan of food, making long-distance storage and transport feasible.<sup>110</sup> Users gained access to a broader range of foods year-round, reducing dependence on local seasonal knowledge.
- *New hygienic and nutritional practices:* Cold storage reduced spoilage and disease. People learned to manage food safety through temperature thresholds and expiration systems rather than sensory evaluation.
- *Controlled indoor environments supporting learning and productivity:* Air conditioning stabilized classroom, workplace, and home environments. Educational and economic activity became less tied to climate variability.<sup>111</sup>
- *Growth of technical expertise in thermodynamics and system maintenance:* Refrigeration and HVAC industries fostered specialized skills in heat transfer, insulation, refrigerants, and mechanical systems.

## Losses

- *Erosion of sensory and ecological food knowledge:* Before refrigeration, people relied on smell, appearance, and context to assess freshness. These competencies declined as sensory judgment was displaced by date labeling and mechanical preservation.
- *Reduced awareness of seasonality:* Year-round availability of foods obscured natural cycles. Knowledge of local harvests, storage methods, and seasonal nutrition weakened.
- *Dependence on energy-intensive infrastructure:* These technologies require electricity, refrigerants, and maintenance. Users become vulnerable to power outages and environmental costs associated with cooling.
- *Narrowing tolerance for heat or cold:* Climate control reduced adaptive bodily responses and resilience to temperature variability, fostering expectations of constant comfort.

Refrigeration and air conditioning stabilized food systems and environments, but detached humans from the sensory, ecological, and practical knowledge once central to survival.

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<sup>110</sup> Freidberg, S. (2009). *Fresh: A perishable history*. Harvard University Press.

<sup>111</sup> Barber, D. A. (2020). *Modern architecture and climate: Design before air conditioning*. Princeton University Press; Banham, R. (1969). *The architecture of the well-tempered environment*. University of Chicago Press.

# Media

## Significance

The evolution from photography to film to digital media transformed how societies document reality, remember events, and construct shared meaning. Images became portable, reproducible, and increasingly manipulable. These technologies reshaped cognitive expectations about evidence, memory, and storytelling. Each medium expanded the capacity to preserve moments and communicate visually, while also altering the competencies required to interpret and trust what is seen.

## Gains

- *Durable, detailed visual records:* Photography provided unprecedented accuracy in documenting landscapes, people, and events. Visual evidence gained epistemic authority in science, journalism, and law.
- *New narrative and analytical tools:* Film introduced motion and sequence, expanding possibilities for explanation and persuasion. Editing techniques fostered new forms of visual literacy—understanding montage, framing, and narrative progression.<sup>112</sup>
- *Democratization of image production:* Digital cameras enabled widespread participation in visual documentation. People learned to compose, edit, and share images as everyday competencies.
- *Enhanced scientific observation:* Slow-motion, time-lapse, and microscopy imaging revealed phenomena previously invisible to the naked eye, expanding scientific understanding.

## Losses

- *Overreliance on visual authority:* Images gained undue credibility, even though composition and framing influence interpretation. The assumption that “seeing is believing” can obscure manipulation.
- *Decline of non-visual knowledge:* As visual documentation became dominant, skills based on memory, descriptive narration, or oral tradition lost ground.
- *Erosion of trust in digital media:* Editing tools and generative technologies blur the line between authentic and fabricated images, requiring new skepticism and verification skills.

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<sup>112</sup> Manovich, L. (2001). *The language of new media*. MIT Press.

- *Attention fragmentation and reduced depth of engagement:* Rapid image consumption can weaken reflective interpretation and reduce the capacity to engage deeply with complex visual materials.

Photography, film, and digital media expanded humanity’s representational toolkit but also introduced new epistemic challenges—especially around interpretation, authenticity, and attentional depth.

## Calculators

### Significance

The widespread adoption of calculators in the 20th century transformed how people engage with numbers, shifting mathematical activity from manual procedures to automated computation.<sup>113</sup> Originally developed for engineering, finance, and scientific work, calculators soon entered schools, workplaces, and homes. Their arrival changed not only the speed and accuracy of calculation but also the structure of mathematical problem-solving itself. Calculators freed learners and professionals from tedious arithmetic, allowing focus on conceptual reasoning—yet they also reshaped expectations about accuracy, mental computation, and what it means to “understand” a mathematical process. In education, the impact on students’ learning and mathematical skills caused significant unrest and controversy. A 2003 meta-analysis of 54 studies on the integration of handheld calculators in instruction and testing reported generally positive effects on students’ operational and mathematical problem-solving skills. Students who used calculators also demonstrated more positive attitudes toward mathematics than those who did not.<sup>114</sup>

### Gains

- *Reduced cognitive load and increased accuracy:* Calculators enable users to perform multi-step or large-number calculations quickly and reliably. This dramatically reduces errors and supports engagement with more advanced

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<sup>113</sup> Houston, K. (2023). *Empire of the Sum: The Rise and Reign of the Pocket Calculator*. New York, NY, USA: W. W. Norton & Company.

<sup>114</sup> Ellington, A. J. (2003). A Meta-Analysis of the Effects of Calculators on Students’ Achievement and Attitude Levels in Precollege Mathematics Classes. *Journal for Research in Mathematics Education*, 34(5), 433–463. <https://doi.org/10.2307/30034795>; Kärchner, H., Trautner, M., Willeke, S., & Schwinger, M. (2022). How handheld use is connected to learning-related factors and academic achievement: Meta-analysis and research synthesis. *Computers and Education Open*, 3, 100116. <https://doi.org/10.1016/J.CAEO.2022.100116>

mathematical ideas, as attention shifts away from mechanical manipulation toward interpretation.

- *Expanded access to quantitative reasoning:* By lowering the barrier posed by arithmetic fluency, calculators allow a broader range of people to participate in numerate tasks. Students who struggle with computation can engage more meaningfully with algebra, geometry, statistics, and modeling earlier and with greater confidence.<sup>115</sup>
- *Enhancement of mathematical exploration:* Calculators make it easy to run comparisons, test hypotheses, and explore patterns. This supports experimental approaches to mathematics, fostering curiosity and iterative thinking.
- *Professionalization and standardization of numeric work:* In fields like engineering, finance, and surveying, calculators standardized calculation practices. Workers developed competencies in interpreting outputs, verifying results, and integrating numerical data into broader decision-making.

## Losses

- *Decline in mental arithmetic and procedural fluency:* As reliance on calculators increased, everyday skills in estimating, checking plausibility, or manipulating numbers mentally became less practiced. This weakens number sense and reduces intuitive understanding of magnitude and proportion.
- *Reduced awareness of mathematical structure:* When calculations are automated, learners may struggle to grasp underlying relationships. The procedural steps that once revealed patterns—carrying, borrowing, factoring—can become opaque.
- *Overconfidence in precise outputs:* Calculator results carry an aura of correctness. Users may trust outputs without evaluating whether inputs were reasonable or whether the operation performed was appropriate.
- *Narrowing of adaptive problem-solving skills:* Mental arithmetic once fostered flexible strategies: approximating, decomposing, or using shortcuts based on context. Dependence on calculators can diminish these adaptive competencies.

Calculators democratized access to complex mathematics and increased accuracy, yet they altered the balance between conceptual insight and procedural understanding. They exemplify how automating a cognitive process can simultaneously enhance and erode mathematical competence.

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<sup>115</sup> Hoyles, C., & Lagrange, J.-B. (Eds.). (2010). *Mathematics education and technology—Rethinking the terrain* (New ICMI Study Series). Springer.

# Computing

## Significance

The emergence of personal computers (PCs) and supercomputers represents one of the most profound technological shifts in human history. Where supercomputers concentrated computational power to model the complexity of the natural and social world, personal computers dispersed that power into homes, schools, and workplaces, transforming everyday cognition and labor. Ordinary people gained access to the tools of creation and analysis that had once been the preserve of specialists. Personal computing replaced passive information consumption with interactive problem-solving. At the same time, supercomputers—gigantic machines capable of trillions of operations per second—extended the epistemic reach of science and engineering. Together, these developments did not merely enhance human productivity; they restructured the *architecture of knowing*. They made possible new forms of distributed cognition and algorithmic reasoning, shifting the boundary between the mental and the mechanical. The result was a dual revolution in skills: at the micro level, humans learned to think with machines; at the macro level, science learned to think at scale.

- *Externalization of cognition*: The personal computer became a cognitive partner—a tool for writing, remembering, and simulating—effectively extending human memory and reasoning capacity.<sup>116</sup>
- *Democratization of computation*: The personal computer made programming and data analysis accessible to millions, decentralizing epistemic agency.
- *Collaborative cognition*: Computers facilitated group work, distributed problem-solving, and collective authorship across institutions and geographies.
- *From factual to procedural knowledge*: Knowing *how* to compute increasingly outweighs knowing *what* to recall.

## Gains

- *Amplified reasoning*: Computers can perform calculations, run simulations, and organize information at speeds the brain cannot match.
- *Computational literacy*: Millions learned programming and data skills, transforming how problems are solved. PCs allowed non-specialists to perform tasks once reserved for experts—statistical analysis, document production, and digital art.

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<sup>116</sup> Salomon, G., Perkins, D.N., & Globerson, T. (1991). Partners in Cognition: Extending Human Intelligence with Intelligent Technologies. *Educational Researcher*, 20(3), 2–9.  
<https://doi.org/10.3102/0013189X020003002>

- *Breakthroughs in science*: Climate models, genomic analysis, and astronomical simulations rely on computational power.
- *Everyday creativity*: Word processors, spreadsheets, and design tools turned ordinary users into creators.
- *Expansion of cognitive bandwidth*: Delegating calculation and data organization to machines freed cognitive space for creativity and interpretation.

## Losses

- *Opacity*: Many algorithms are “black boxes”—we see outputs, not the reasoning behind them.<sup>117</sup>
- *Deskilling*: Computational digital tools can erode mental arithmetic or intuitive understanding.
- *Unequal access*: Nations and institutions without high-performance computing fall behind in science and innovation, widening divides.
- *False certainty*: Computational precision can be mistaken for truth even when models rest on uncertain assumptions.<sup>118</sup>

## Internet

### Significance

Emerging from Cold War networking experiments and maturing through the World Wide Web, the Internet transformed knowledge from a static archive into a dynamic, interconnected system. It dissolved boundaries between producers and consumers of information, establishing a global, decentralized infrastructure for communication and collaboration.<sup>119</sup> The Internet transformed the way we live and use knowledge in our daily lives. It has even changed how future couples meet: Internet meetings are displacing the roles that family and friends once played in bringing couples together.<sup>120</sup> The Internet’s epistemic essence lies in its networked architecture: hyperlinks, protocols, and platforms that connect people, documents, and data in real time. It

<sup>117</sup> Humphreys, P. (2009). The philosophical novelty of computer simulation methods. *Synthese* 169, 615–626. <https://doi.org/10.1007/s11229-008-9435-2>

<sup>118</sup> Van Dijk, J. (2020). *The digital divide*. Polity Press.

<sup>119</sup> Heersmink, R., & Sutton, J. (2020). Cognition and the Web: Extended, Transactive, or Scaffolded? *Erkenntnis*, 85(1), 139–164. <https://doi.org/10.1007/s10670-018-0022-8>

<sup>120</sup> Rosenfeld, M. J., Thomas, R. J., & Hausen, S. (2019). Disintermediating your friends: How online dating in the United States displaces other ways of meeting. *Proceedings of the National Academy of Sciences*, 116(36), 17753–17758. <https://doi.org/10.1073/pnas.1908630116>

replaced the scarcity of information with its overabundance, making navigation, not acquisition, the core cognitive task of the modern age.

- *Fastest possible transmission*: From books at airplane speed to terabytes/second.
- *From transmission to interaction*: Knowledge shifted from one-way broadcasting to participatory exchange.
- *Decentralization of authority*: Power moved from traditional gatekeepers (universities, publishers) to networks and algorithms.
- *Hyperconnectivity as epistemic medium*: Search engines and hyperlinks turned knowledge into an evolving, relational web.
- *Digital permanence and immediacy*: Information became globally accessible and temporally persistent, collapsing spatial barriers.

## Gains

- *Unprecedented access*: Education, research, and communication became available to anyone with a connection.
- *Collective learning*: Platforms like Wikipedia and open-source communities let ordinary people contribute to knowledge.<sup>121</sup>
- *New literacies*: The ability to *search, find, evaluate, and synthesize* information became as crucial as knowing facts themselves. Information literacy expanded into media literacy and data literacy.
- *Faster collaboration*: Scientists, teachers, and activists can work together across continents in real time.
- *Transparency and openness*. Open science, open data, and citizen journalism expanded the scope of verification and participation.

## Losses

- *Reduced likelihood of storing information in memory*: By making information retrievability salient, Internet search reduces the likelihood of information being stored in memory. Furthermore, online searching leads to the misattribution of information to internal memory, thereby masking Internet-induced learning deficits.<sup>122</sup>
- *Misinformation*: False or misleading content can spread faster than corrections.<sup>123</sup>
- *Algorithmic gatekeeping*: Search engines shape what we see—and what we don't.

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<sup>121</sup> Benkler, Y. (2006). *The wealth of networks: How social production transforms markets and freedom*. Yale University Press.

<sup>122</sup> Fisher, M., Smiley, A. H., & Grillo, T. L. H. (2022). Information without knowledge: the effects of Internet search on learning. *Memory*, 30(4), 375–387. <https://doi.org/10.1080/09658211.2021.1882501>

<sup>123</sup> Vosoughi, S., Roy, D., & Aral, S. (2018). The spread of true and false news online. *Science*, 359(6380), 1146–1151. <https://doi.org/10.1126/science.aap9559>

- *Erosion of epistemic trust*: The flood of information blurs distinctions between expert and lay knowledge.
- *Fragmented attention*: The constantly evolving stream of online information divides our attention across multiple media sources, at the expense of sustained concentration.<sup>124</sup>
- *Cognitive overload*: Continuous streams of data challenge attention, retention, and reflection and constrain the cognitive enhancement that the Internet promises.<sup>125</sup>
- *Digital divides*: Access does not guarantee skill; inequalities persist in digital literacy and critical evaluation.

## GPS

### Significance

Global Positioning System (GPS) technology has revolutionized navigation by providing real-time, turn-by-turn directions accessible to anyone with a GPS receiver. By combining satellite networks, digital maps, and automated routing, GPS shifted the skill of navigation from an embodied, interpretive practice to a largely outsourced function. Before GPS, navigation relied on spatial memory, local knowledge, and continuous interpretation of terrain and landmarks. With GPS, navigation is increasingly algorithmic, abstract, and detached from direct environmental cues. This shift has profound epistemic consequences for how individuals and societies understand space, movement, and place. Today, GPS is no longer perceived as an extraordinary technology; rather, it is an invisible background system that organizes logistics, transport, communication, and even personal identity in space.

### Gains

- *Increased accuracy and efficiency of movement*: GPS provides precise locations and optimized routes, reducing travel time and uncertainty. Users gain confidence in exploring unfamiliar areas, expanding practical mobility and reducing cognitive stress.<sup>126</sup>
- *Lower barrier to participation in navigation tasks*: Individuals with limited spatial-awareness skills can navigate complex environments. This democratizes

<sup>124</sup> Firth, J., Torous, J., Stubbs, B., Firth, J.A., Steiner, G.Z., Smith, L., Alvarez-Jimenez, M., Gleeson, J., Vancampfort, D., Armitage, C.J. and Sarris, J. (2019). The “online brain”: how the Internet may be changing our cognition. *World Psychiatry*, 18: 119-129. <https://doi.org/10.1002/wps.20617>

<sup>125</sup> Voinea, C., Vică, C., Mihailov, E., & Savulescu, J. (2020). The Internet as Cognitive Enhancement. *Science and Engineering Ethics*, 26(4), 2345–2362. <https://doi.org/10.1007/s11948-020-00210-8>

<sup>126</sup> Ishikawa, T., Fujiwara, H., Imai, O., & Okabe, A. (2008). Wayfinding with a GPS-based mobile navigation system: A comparison with maps and direct experience. *Journal of Environmental Psychology*, 28(1), 74–82. <https://doi.org/https://doi.org/10.1016/j.jenvp.2007.09.002>

mobility and benefits travelers, workers, and emergency responders. Interfaces progressed from static cartography to turn-by-turn instructions, offloading route computation and micro-decisions to algorithms.<sup>127</sup>

- *Integration with digital mapping and real-time data:* GPS systems incorporate traffic conditions, road closures, and alternative routes. Users develop competencies in interpreting layered data—timing, congestion, hazards—and integrating it into decision-making.
- *New professional and scientific applications:* Fields like surveying, agriculture, logistics, and ecology rely on GPS to track movement, coordinate fleets, and monitor environmental change. These uses expand analytical and geospatial skills beyond traditional cartography.

## Losses

- *Decline of spatial literacy and embodied knowing:* The most discussed epistemic cost of GPS is cognitive: people who depend on GPS form weaker “cognitive maps” of their environments.<sup>128</sup> Experiments show that GPS-guided navigation leads to significantly poorer recall of landmarks, route topology, and environmental structure compared to map-based or self-directed navigation.<sup>129</sup> A study showed that using a turn-by-turn navigation system negates route learning and impairs scene recognition, suggesting that using a navigation system while driving creates inattention blindness, a failure to “see” elements in the environment.<sup>130</sup>
- *Reduced interpretive engagement with surroundings:* GPS encourages “following instructions” rather than reading terrain. The focus shifts from situational

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<sup>127</sup> Clemenson, G. D., Maselli, A., Fiannaca, A. J., Miller, A., & Gonzalez-Franco, M. (2021). Rethinking GPS navigation: creating cognitive maps through auditory clues. *Scientific Reports*, 11(1), 7764.

<https://doi.org/10.1038/s41598-021-87148-4>

<sup>128</sup> Miola, L., Muffato, V., Sella, E., Meneghetti, C., & Pazzaglia, F. (2024). GPS use and navigation ability: A systematic review and meta-analysis. *Journal of Environmental Psychology*, 99, 102417.

<https://doi.org/https://doi.org/10.1016/j.jenvp.2024.102417>; Dahmani, L., & Bohbot, V. D. (2020). Habitual use of GPS negatively impacts spatial memory during self-guided navigation. *Scientific Reports*, 10, 6310.

<https://doi.org/10.1038/s41598-020-62877-0>; Zisch, F., et al. (2021). Rethinking GPS navigation: Creating cognitive maps through auditory beaconing. *Scientific Reports*, 11, 6965.

<https://doi.org/10.1038/s41598-021-87148-4>

<sup>129</sup> Ruginski, I. T., Creem-Regehr, S. H., Stefanucci, J. K., & Cashdan, E. (2019). GPS use negatively affects environmental learning through spatial transformation abilities. *Journal of Environmental Psychology*, 64, 12–20. <https://doi.org/https://doi.org/10.1016/j.jenvp.2019.05.001>; Topete, A., He, C., Protzko, J., Schooler, J., & Hegarty, M. (2024). How is GPS used? Understanding navigation system use and its relation to spatial ability. *Cognitive Research: Principles and Implications*, 9(1), 16.

<https://doi.org/10.1186/s41235-024-00545-x>

<sup>130</sup> Fenech, E. P., Drews, F. A., & Bakdash, J. Z. (2010). The Effects of Acoustic Turn-by-turn Navigation on Wayfinding. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, 54(23), 1926-1930. <https://doi.org/10.1177/154193121005402305>

awareness to monitoring a screen, narrowing attention to a simplified, abstracted view of space.

- *Vulnerability to system errors and outages:* GPS can fail due to signal loss, outdated maps, or algorithmic mistakes. Without traditional navigation skills, users may be unable to compensate or detect inaccuracies.
- *Homogenization of experience and route selection:* GPS tends to prioritize efficiency, directing travelers along similar paths. This reduces exposure to diverse environments and diminishes incidental learning about geography, culture, and landscape.

GPS improved navigational accuracy and broadened mobility, yet it weakened embodied spatial knowledge and fostered new dependencies on digital infrastructure. It represents a shift from experiential navigation to algorithmic guidance, altering how people perceive and inhabit physical space.

## Smartphones

### Significance

The smartphone combined the strengths of earlier technologies—telephony, computing, and the internet—into a single, always-available device. For billions of people, it became the primary gateway to information, communication, and even navigation. Smartphones did not simply add convenience—they changed the conditions under which people think. Cognition became mobile, lightweight, and intertwined with the flow of daily life. The smartphone personalized the internet, transforming it from an external network into a constant companion and extension of the human body and mind. In many more and different ways than the computer, the smartphone impacted human cognition.<sup>131</sup>

- *Ubiquity & “always-on” access:* by today, smartphones are near-universal in many countries and people report being online “almost constantly.”<sup>132</sup>
- *Miniaturized convergence:* Smartphones integrate phone calls, photography, messaging, navigation, and computing into one handheld device.
- *Permanent connectivity:* Continuous mobile internet access created an “always-on” epistemic environment where information and communication became instantaneous.

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<sup>131</sup> Huber, L. (2015). *Otto’s Notebook vs the Memex: Comparing the smartphone and the PC as two paradigms of cognitive enhancement*. <https://hdl.handle.net/10822/761435>

<sup>132</sup> Pew Research Center (2024). *Mobile Fact Sheet*. <https://www.pewresearch.org/internet/fact-sheet/mobile/>

- *Embodied interface*: Touchscreens, voice assistants, and haptic feedback made interaction intuitive and bodily, reducing the cognitive distance between human and machine.
- *Everyday transactive memory*: Users rely on smartphones as external repositories, remembering where information is stored (e.g., Google, Notes, Messages) rather than the content itself.<sup>133</sup>
- *Platformization of knowledge*: knowledge flows became dependent on algorithmic intermediaries—search engines, feeds, app ecosystems—that shape what users know and how they know it.<sup>134</sup>

## Gains

- *Instant knowledge*: The smartphone provides real-time, context-sensitive knowledge (e.g., traffic, translation, weather, directions) that supports adaptive decision-making.
- *Multimodal literacy*: Ordinary people now master hybrid literacies—visual, auditory, gestural—due to camera use, voice notes, emojis, and short-form video.
- *Microlearning culture*: Short videos, podcasts, and interactive mobile lessons made informal, spontaneous learning part of everyday commutes or breaks.<sup>135</sup>
- *Instant translation and cross-lingual cognition*: Apps like Google Translate and real-time captions expanded multilingual communication but reduced language-learning persistence.
- *Everyday creativity*: Cameras and editing apps allow anyone to document and share their world.

## Losses

- *Cognitive erosion*: While the evidence is still limited and mixed, there are strong indications that cognitive functioning is affected by smartphone usage.<sup>136</sup> Instead of deliberate research, quick mobile searches supply “good-enough” answers for

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<sup>133</sup> Sparrow et al. (2011).

<sup>134</sup> van Dijck, J., Poell, T., & de Waal, M. (2018). *The Platform Society: Public values in a connective world*. Oxford University Press.

<sup>135</sup> Traxler, J. (2007). Defining, Discussing and Evaluating Mobile Learning: The moving finger writes and having writ . . . . *The International Review of Research in Open and Distributed Learning*, 8(2).

<https://doi.org/10.19173/irrodl.v8i2.346>

<sup>136</sup> Wilmer, H. H., Sherman, L. E., & Chein, J. M. (2017). Smartphones and Cognition: A Review of Research Exploring the Links between Mobile Technology Habits and Cognitive Functioning. *Frontiers in Psychology*, Volume 8-2017. <https://www.frontiersin.org/journals/psychology/articles/10.3389/fpsyg.2017.00605>;

Parry, D. A. (2023). Does the Mere Presence of a Smartphone Impact Cognitive Performance? A Meta-Analysis of the “Brain Drain Effect.” *Media Psychology*, 27(5), 737–762.

<https://doi.org/10.1080/15213269.2023.2286647>.

decision-making in real time.<sup>137</sup> A recent randomized controlled trial, in which the “smart” features of phones were blocked, demonstrated that the intervention improved mental health, well-being, and attention, primarily by influencing how people spent their time.<sup>138</sup> In the case of translation, a recent study found that while deskillling is not the primary issue, the primary issue is students’ ability to deploy critical strategies.<sup>139</sup>

- *Shallow processing*: Easy retrieval discourages long-term retention or critical reflection, reinforcing surface-level understanding.<sup>140</sup> Another study identified significant differences between high and low smartphone users in critical thinking, specifically in their abilities to evaluate sources.<sup>141</sup>
- *Digital inequality*: Access to smartphones may be widespread, but epistemic benefits vary by digital literacy, socioeconomic status, and infrastructure.

## Social media

### Significance

Before social media, most people encountered public knowledge through a few gatekeeper channels—papers, radio, TV, maybe a blog or forum if you were keen. Social media rewired that entire pathway. Now, what you “know” is not just what’s published but what your network surfaces and what the recommender decides is likely to hold your attention. The big leap isn’t the device—it’s the programmable public sphere where visibility, sequence, and salience of information are continuously personalized and optimized for engagement. In practice, this means that each person’s reality is subtly reordered in real time, making social discovery—not scheduled broadcasts—the default way ordinary people encounter facts, frames, and explanations. Social media created a new kind of public sphere—participatory, personalized, and fast-moving—where

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<sup>137</sup> Barr, N., Pennycook, G., Stolz, J. A., & Fugelsang, J. A. (2015). The brain in your pocket: Evidence that smartphones are used to supplant thinking. *Computers in Human Behavior*, *48*, 473–480. <https://doi.org/10.1016/j.chb.2015.02.029>

<sup>138</sup> Castelo, N., Kushlev, K., Ward, A. F., Esterman, M., & Reiner, P. B. (2025). Blocking mobile internet on smartphones improves sustained attention, mental health, and subjective well-being. *PNAS Nexus*, *4*(2), pgaf017. <https://doi.org/10.1093/pnasnexus/pgaf017>

<sup>139</sup> Musk, N., & van der Meij, S. (2024). Critical interactional strategies for selecting candidate translations in online translation tools in collaborative EFL writing tasks. *Linguistics and Education*, *80*, 101290. <https://doi.org/https://doi.org/10.1016/j.linged.2024.101290>

<sup>140</sup> Barr et al (2015); Aru, J., & Rozgonjuk, D. (2022). The effect of smartphone use on mental effort, learning, and creativity. *Trends in Cognitive Sciences*, *26*(10), 821–823. <https://doi.org/10.1016/j.tics.2022.07.002>

<sup>141</sup> Fabio, R. A., & Suriano, R. (2023). The Influence of Smartphone Use on Tweens’ Capacity for Complex Critical Thinking. *Children*, *10*(4), 698. <https://doi.org/10.3390/children10040698>

information travels through social networks rather than institutions. It empowers individuals but complicates society's ability to agree on what is true.

- *Core innovation*: Algorithmic curation (ranking, recommendation, amplification) personalizes what each person sees, creating platform-made information diets and “echo chambers.”<sup>142</sup>
- *Everyday sense-making becomes social*: People learn by observing peers' takes, reposts, and notes; social proof becomes a default heuristic for plausibility.
- *Gatekeeping shift*: From newsroom editors to platform governance and creator networks.<sup>143</sup>
- *New intermediaries*: Influencers and independent “news creators” emerge as attention brokers; for younger users they rival or surpass journalists as news sources.

## Gains

- *Diverse voices*: Marginalized perspectives and lived experiences can reach global audiences.
- *Collective sense-making*: People debate, annotate, correct, and share information with peers. Community fact-checking can measurably reduce low-quality sharing and increase trust in corrections (though not perfectly or instantly).<sup>144</sup>
- *New literacies*: Feed literacy (how ranking works, what “for you” means), source triangulation on the fly (clicking through, lateral reading, checking community notes/fact-checks), audience management under context collapse (anticipating mixed audiences).
- *Community mobilization*: Social media enables rapid coordination during crises and social movements.

## Losses

- *Amplification of falsehoods*: Emotionally charged or sensational content spreads more quickly than factual reporting.<sup>145</sup>

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<sup>142</sup> Cinelli, M., de Francisci Morales, G., Galeazzi, A., Quattrociocchi, W., & Starnini, M. (2021). The echo chamber effect on social media. *Proceedings of the National Academy of Sciences*, 118(9), e2023301118. <https://doi.org/10.1073/pnas.2023301118>

<sup>143</sup> Nieborg, D. B., & Poell, T. (2018). The platformization of cultural production: Theorizing the contingent cultural commodity. *New Media & Society*, 20(11), 4275-4292. <https://doi.org/10.1177/1461444818769694>

<sup>144</sup> Drolsbach, C. P., Solovev, K., & Pröllochs, N. (2024). Community notes increase trust in fact-checking on social media. *PNAS Nexus*, 3(7), pgae217. <https://doi.org/10.1093/pnasnexus/pgae217>

<sup>145</sup> Vosoughi, S., Roy, D., & Aral, S. (2018). The spread of true and false news online. *Science*, 359(6380), 1146–1151. <https://doi.org/10.1126/science.aap9559>

- *Echo-/filter dynamics and affective polarization*: Effects are mixed across platforms and people, but partisan echo chambers and exposure to hostile out-group content can heighten polarization.<sup>146</sup> Political polarization coincided with the advent of social media.<sup>147</sup>
- *Erosion of trust & well-being links*: Competing claims and comparison dynamics can undermine trust and self-assessment, with heterogeneous effects across users.<sup>148</sup>
- *Cognitive overload*: Endless scrolling rewards speed over reflection and encourages quick judgments.
- *Decreased academic performance*: Intensive app usage affects academic outcomes. A recent study of Chinese students found that a one-standard-deviation increase in app usage lowers academic test scores by 36%.<sup>149</sup> Another study demonstrated that increases in social media use during early adolescence were significantly associated with lower performance on specific aspects of cognitive function. However, overall differences in mean scores were relatively small.<sup>150</sup> Furthermore, the impact of social media usage on academic performance is mediated by parent-adolescent communication.<sup>151</sup>
- *Loss of empathy*: The advent of social media has resulted in human beings preferring engagement in mediated communications. This results in reduced reliance on the five primary senses acting in concert during social interaction, a key to empathy. The result may be less honest relationships.<sup>152</sup>
- *Moderation/fact-checking limits*: Traditional fact-checks often have modest impact on sharing/belief change; timing and perceived neutrality matter.<sup>153</sup>

<sup>146</sup> Hobolt, S. B., Lawall, K., & Tilley, J. (2024). The Polarizing Effect of Partisan Echo Chambers. *American Political Science Review*, 118(3), 1464–1479. <https://doi.org/10.1017/S0003055423001211>

<sup>147</sup> Thurner, S., Hofer, M., & Korb, J. (2025). Why more social interactions lead to more polarization in societies. *Proceedings of the National Academy of Sciences*, 122(44), e2517530122. <https://doi.org/10.1073/pnas.2517530122>

<sup>148</sup> Sharon, T., & Encarnación, M. (2024). Social Media & Declining Trust: An Epistemic Challenge for Emerging Adults? *Emerging Adulthood*, 12(3), 358-371. <https://doi.org/10.1177/21676968241234091>;

Meier, A., & Johnson, B. K. (2022). Social comparison and envy on social media: A critical review. *Current Opinion in Psychology*, 45, 101302. <https://doi.org/https://doi.org/10.1016/j.copsy.2022.101302>

<sup>149</sup> Barwick, P. J., Chen, S., Fu, C., & Li, T. (2024). *Digital Distractions with Peer Influence: The Impact of Mobile App Usage on Academic and Labor Market Outcomes*. <https://doi.org/10.3386/w33054>

<sup>150</sup> Nagata, J. M., Wong, J. H., Kim, K. E., Richardson, R. A., Nayak, S., Potes, C., Rauschecker, A. M., Scheffler, A., Sugrue, L. P., Baker, F. C., & Testa, A. (2025). Social Media Use Trajectories and Cognitive Performance in Adolescents. *JAMA*, 334(21), 1948–1950. <https://doi.org/10.1001/jama.2025.16613>

<sup>151</sup> Gordon, M. S., & Ohannessian, C. M. (2023). Social Media Use and Early Adolescents' Academic Achievement: Variations by Parent-Adolescent Communication and Gender. *Youth & Society*, 56(4), 651-672. <https://doi.org/10.1177/0044118X231180317>

<sup>152</sup> Wagner, L.A. (2015). When Your Smartphone Is Too Smart for Your Own Good: How Social Media Alters Human Relationships. *The Journal of Individual Psychology* 71(2), 114-121. <https://dx.doi.org/10.1353/jip.2015.0009>.

<sup>153</sup> Liu, X., Qi, L., Wang, L., & Metzger, M. J. (2023). Checking the Fact-Checkers: The Role of Source Type, Perceived Credibility, and Individual Differences in Fact-Checking Effectiveness. *Communication Research*, 52(6), 719-746. <https://doi.org/10.1177/00936502231206419>

- *Challenge of epistemic vigilance:* Users often lack the material means to be epistemically vigilant. Mere social media literacy (or individual fact-checking) is insufficient because such strategies tend to place the burden on users and are especially difficult for less privileged users with fewer cognitive/epistemic resources.<sup>154</sup>

## Artificial intelligence

### Significance

The emergence of artificial intelligence, particularly through machine learning (ML) and large language models (LLMs), represents a qualitative shift in how knowledge is processed and generated. Earlier computational systems primarily performed symbolic manipulation or retrieval—they indexed and searched information created by humans. In contrast, modern generative models encode the statistical regularities of vast corpora and can synthesize novel, contextually relevant outputs in natural language, images, or code. LLMs are multifunctional computational cognitive artifacts used for various cognitive tasks, including translation, summarization, question answering, and information retrieval. This transition marks the movement from “informational technologies” to “epistemic technologies,” in which machines participate in meaning-making rather than merely storing or transmitting data. It is this generative and interpretive capacity that underpins the present epistemic transformation.

- *From retrieval to generation:* LLMs compress vast text corpora into models that can synthesize explanations, drafts, and step-by-step guidance on demand—an interface shift from *search engines* to *answer engines*.<sup>155</sup>
- *Cognitive artifact at scale:* LLMs function as general-purpose *cognitive tools* for summarizing, translating, brainstorming, tutoring, coding, planning—usable by non-experts.<sup>156</sup>
- *Everyday augmentation:* Controlled studies show big productivity boosts for routine knowledge work (especially for novices), indicating that generative AI acts as training wheels and accelerator.<sup>157</sup>

<sup>154</sup> Mattioni, M. (2024). Is Epistemic Autonomy Technologically Possible Within Social Media? A Socio-Epistemological Investigation of the Epistemic Opacity of Social Media Platforms. *Topoi*, 43(5), 1503–1516. <https://doi.org/10.1007/s11245-024-10107-x>

<sup>155</sup> Liu, L., Meng, J., & Yang, Y. (2024). LLM technologies and information search. *Journal of Economy and Technology*, 2, 269–277. <https://doi.org/https://doi.org/10.1016/j.ject.2024.08.007>

<sup>156</sup> Heersmink, R., de Rooij, B., Clavel Vázquez, M. J., & Colombo, M. (2024). A phenomenology and epistemology of large language models: transparency, trust, and trustworthiness. *Ethics and Information Technology*, 26(3), 41. <https://doi.org/10.1007/s10676-024-09777-3>

<sup>157</sup> Brynjolfsson, E., Li, D., & Raymond, L. (2025). Generative AI at Work. *The Quarterly Journal of Economics*, 140(2), 889–942. <https://doi.org/10.1093/qje/qjae044>; Noy, S., & Zhang, W. (2023).

- *Platform-level gatekeeping*: As AI mediates what we see and how it's phrased, recommendation, summarization, and chatbot layers become new *gatekeepers* of public knowledge. There is a robust and growing movement toward Content Credentials/C2PA to attach verifiable source and edit histories to digital media, driven by the urgent need to combat misinformation.<sup>158</sup> The movement is evidenced by multiple industry and academic efforts: C2PA has developed specifications for provenance tracking across images,<sup>159</sup> videos,<sup>160</sup> audio, and documents.
- *Regulatory guardrails*: Regulatory frameworks, such as the EU AI Act, introduce tiered risk obligations and transparency duties (e.g., letting users know they're interacting with AI; stricter rules for high-risk and systemic-risk models), pushing platforms toward auditable practices.

It is still very early to assess the impact of AI on human cognitive behavior and competencies. Research on this topic is only beginning, so what we can learn from the research literature on gains and losses remains preliminary.

## Gains

- *Access, acceleration, and efficiency*: Lower language and expertise barriers; AI systems significantly reduce cognitive load in tasks such as searching, summarizing, translating, and problem-solving. By externalizing these processes, users can reallocate cognitive effort toward higher-order reasoning, synthesis, and creativity.
- *Speed & scaffolding*: Faster drafting, ideation, and tutoring raise throughput and can upskill novices in the flow of work, increasing productivity.
- *Expansion of epistemic reach and inclusion*: LLMs provide access to specialized knowledge that previously required formal training or linguistic fluency. They can act as universal explainers, generating context-sensitive and accessible accounts of complex concepts. This capability enhances epistemic inclusion, particularly for non-native speakers and learners outside institutional education systems.
- *Personalization and control in learning*: Through adaptive dialogue, AI tools support personalized learning pathways. They adjust explanations to users' prior understanding, thereby improving knowledge retention and engagement. This

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Experimental evidence on the productivity effects of generative artificial intelligence. *Science*, 381(6654), 187–192. <https://doi.org/10.1126/science.adh2586>

<sup>158</sup> Castellanos, J., & Gulliford (Kearns), S. (2022). Layers of Trust. *Commonplace*. <https://doi.org/10.21428/6ffd8432.3b76421c>

<sup>159</sup> Temmermans, F., & Rosenthol, L. (2021). Adopting the JPEG universal metadata box format for media authenticity annotations. *Proc.SPIE*, 11842, 118420M. <https://doi.org/10.1117/12.2597651>

<sup>160</sup> Petrangeli, S., Wang, H., Fisher, M., Kozma, D., Mahamli, M., Blumenthal, P., & Parsons, A. (2024). Integrating Content Authenticity with DASH Video Streaming. *Proceedings of the 15th ACM Multimedia Systems Conference*, 492–498. <https://doi.org/10.1145/3625468.3652198>

dialogic feedback structure approximates one-on-one tutoring, long recognized as the most effective pedagogical form.

- *Productivity and learning boosts*: LLM feedback can accelerate practice (e.g., clinical decision-making exercises), though effects vary by task and expertise.<sup>161</sup> In education, early RCTs suggest AI instructors can increase perceived learner control and performance in some settings.<sup>162</sup>
- *Cognitive scaffolding and meta-reflection*: By providing immediate feedback, LLMs foster meta-cognitive awareness—users can see their reasoning mirrored, corrected, or rephrased in real time. This iterative engagement promotes self-explanation and reflection, processes known to enhance durable understanding and transfer of knowledge.
- *Augmentation of creative and inferential capacities*: AI can generate analogies, alternative framings, or counterfactuals that extend human imagination. This form of “computational serendipity” broadens conceptual exploration and supports creative synthesis across disciplines.<sup>163</sup>

## Losses

- *Opacity and loss of epistemic traceability*: The internal reasoning of generative models is non-transparent even to experts. For users, this opacity obstructs the reconstruction of why an answer is plausible, preventing evaluation based on source provenance or inferential validity. This undermines one of the core virtues of knowledge: its accountability to reasons. As AI curates and composes what we see, opacity about sources, ranking, and generation pipelines can concentrate epistemic authority in platforms.
- *Generalization bias, distortion and hallucination of information*: LLMs often *oversimplify* or *overgeneralize* scientific and factual claims—even more when asked to be “accurate,” creating confident wrongness for lay readers. Generative systems produce plausible fabrications—syntactically and semantically coherent statements that lack factual grounding. For non-expert users, these “hallucinations” blur distinctions between knowledge and conjecture, eroding epistemic reliability at the point of consumption.<sup>164</sup>

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<sup>161</sup> de Barros, E. C. (2024). Understanding the influence of digital technology on human cognitive functions: A narrative review. *IBRO Neuroscience Reports*, 17, 415–422.

<https://doi.org/https://doi.org/10.1016/j.ibneur.2024.11.006>

<sup>162</sup> Qin, F., Hao, Z., Yu, J., Liu, Z., & Zhang, Y. (2025). AI instructional agent improves student's perceived learner control and learning outcome: empirical evidence from a randomized controlled trial. *ArXiv*.

<https://doi.org/10.48550/arXiv.2505.22526>

<sup>163</sup> Mugleston, J., Truong, V. H., Kuang, C., Sibiya, L., & Myung, J. (2025). Epistemology in the Age of Large Language Models. *Knowledge*, 5(1), 3. <https://doi.org/10.3390/knowledge5010003>

<sup>164</sup> Peterson, A. J. (2025). AI and the problem of knowledge collapse. *AI & SOCIETY*, 40(5), 3249–3269. <https://doi.org/10.1007/s00146-024-02173-x>; Wright, D., Masud, S., Moore, J., Yadav, S., Antoniak, M.,

- *Cognitive offloading*: Routine recall, drafting, translation, and coding are increasingly offloaded to AI, changing the balance between internal memory and external tools; early studies link heavy AI use to shifts in critical-thinking effort.<sup>165</sup> By incorporating technological tools into "neural niche," the brain can undergo structural transformation.<sup>166</sup> Continuous delegation of cognitive tasks to AI can lead to skill atrophy—the gradual decline in memory, synthesis, and analytic reasoning due to externalization of effort.<sup>167</sup> This risk mirrors earlier effects observed with calculators and GPS technologies but now extends into conceptual and linguistic domains.
- *Possible negative impact on human creativity*: Recent research revealed that while LLM assistance can provide short-term boosts in creativity during assisted tasks, it may inadvertently hinder independent creative performance when users work without assistance, raising concerns about the long-term impact on human creativity and cognition.<sup>168</sup>
- *Erosion of epistemic vigilance and critical reasoning*: The fluency and authority of AI-generated text can suppress users' natural skepticism. Overreliance may lead to automation bias, where individuals defer to outputs without adequate verification. This weakens epistemic vigilance and undermines the capacity to assess credibility and evidential grounding. Recent research has found that higher AI literacy and higher confidence in one's performance with AI are associated with lower metacognitive accuracy.<sup>169</sup>

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Park, C.Y., & Augenstein, I. (2025). Epistemic Diversity and Knowledge Collapse in Large Language Models. *ArXiv*.

<https://doi.org/10.48550/arXiv.2510.04226>

<sup>165</sup> Gerlich, M. (2025). AI Tools in Society: Impacts on Cognitive Offloading and the Future of Critical Thinking. *Societies*, 15(1), 6. <https://doi.org/10.3390/soc15010006>

<sup>166</sup> León-Domínguez, U. (2024). Potential cognitive risks of generative transformer-based AI chatbots on higher order executive functions. *Neuropsychology*, 38(4), 293–308. <https://doi.org/10.1037/neu0000948>

<sup>167</sup> Oakley, B., Johnston, M., Chen, K., Jung, E., & Sejnowski, T.J. (2025). The Memory Paradox: Why Our Brains Need Knowledge in an Age of AI. *ArXiv*. <https://doi.org/10.48550/arXiv.2506.11015>; Macnamara, B.

N., Berber, I., Çavuşoğlu, M. C., Krupinski, E. A., Nallapareddy, N., Nelson, N. E., Smith, P. J., Wilson-Delfosse, A. L., & Ray, S. (2024). Does using artificial intelligence assistance accelerate skill decay and hinder skill development without performers' awareness? *Cognitive Research: Principles and Implications*, 9(1), 46. <https://doi.org/10.1186/s41235-024-00572-8>; Kosmyna, N., Hauptmann, E., Yuan, Y.

T., Situ, J., Liao, X.-H., Beresnitzky, A. V., Braunstein, I., & Maes, P. (2025). Your Brain on ChatGPT: Accumulation of Cognitive Debt when Using an AI Assistant for Essay Writing Task. *ArXiv*,

[abs/2506.08872](https://doi.org/10.48550/arXiv.2506.08872). <https://api.semanticscholar.org/CorpusID:279261394>

<sup>168</sup> Kumar, H., Vincentius, J., Jordan, E., & Anderson, A. (2025). Human creativity in the age of LLMs: Randomized experiments on divergent and convergent thinking. *Proceedings of the 2025 CHI Conference on Human Factors in Computing Systems* (pp. 1-18). <https://doi.org/10.48550/arXiv.2410.03703>

<sup>169</sup> Fernandes, D., Villa, S., Nicholls, S., Haavisto, O., Buschek, D., Schmidt, A., Kosch, T., Shen, C., & Welsch, R. (2026). AI makes you smarter but none the wiser: The disconnect between performance and metacognition. *Computers in Human Behavior*, 175, 108779.

[https://doi.org/https://doi.org/10.1016/j.chb.2025.108779](https://doi.org/10.1016/j.chb.2025.108779)

- *Affective and motivational consequences:* The perceived completeness and immediacy of AI explanations can create a false sense of mastery, reducing intrinsic motivation to explore further sources or engage in deep study. AI explanations can create an illusion of understanding that paradoxically reduces motivation to explore and understand deeply, potentially undermining genuine learning processes. AI technologies like ChatGPT may trigger “metacognitive laziness,” potentially hindering self-regulation and deep learning.<sup>170</sup> Conversely, when confronted with model uncertainty, some users may experience epistemic disorientation or distrust toward both human and algorithmic knowledge.
- *Weaker coping mechanisms:* AI usage and the cognitive offloading associated with it might weaken the coping mechanisms against stress and mental health issues by eroding introspection, outsourcing resilience, or generating additional anxiety.<sup>171</sup>
- *Homogenization:* Because models learn from large corpora, they may reproduce mainstream ideas while muting minority perspectives.<sup>172</sup> As users increasingly consult a small number of generative systems, informational ecosystems may converge toward narrower worldviews.

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<sup>170</sup> Fan, Y., Tang, L., Le, H., Shen, K., Tan, S., Zhao, Y., Shen, Y., Li, X., & Gašević, D. (2025). Beware of metacognitive laziness: Effects of generative artificial intelligence on learning motivation, processes, and performance. *British Journal of Educational Technology*, 56, 489–530. <https://doi.org/10.1111/bjet.13544>

<sup>171</sup> Chirayath, G., Premamalini, K., & Joseph, J. (2025). Cognitive offloading or cognitive overload? How AI alters the mental architecture of coping. *Frontiers in Psychology*, Volume 16-2025. <https://www.frontiersin.org/journals/psychology/articles/10.3389/fpsyg.2025.1699320>

<sup>172</sup> Peters, U., & Chin-Yee, B. (2025). Generalization bias in large language model summarization of scientific research. *Royal Society Open Science*, 12(4), 241776. <https://doi.org/10.1098/rsos.241776>