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# Integrating systems and design thinking: A neuroscience perspective

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*The rapidity with which complex systems shape and impact actuality and human experience is unprecedented and undeniably a salient feature of today's world. The COVID-19 pandemic continues to unravel the ripple effects of interrelated and interdependent systems wherein changes in one part, impact, to a greater or lesser degree, all parts of the whole. The impact across multiple domains, sectors and demographics has accentuated the need for design and designers to embrace systems-based thinking to facilitate, enable and enhance their design practice and the systemic value of design.*

*The term systems thinking is used to refer to the cognitive competencies of designers as identified by cognitive psychologists and neuroscientists. The term systemic design refers to the application of these cognitive competencies to co-creating adaptable and innovative solutions to complex and wicked problems.*

*In a world where systems are intricately interconnected, the finely tuned responsiveness of the people-centred inclusive designer, is ushered headlong into the world of systems thinking with its non-reductionist challenges of holism, connectivity, dynamic emergence, and ripple effect phenomena. The pressure this brings to bear on designers to incorporate multidisciplinary perspectives in their designerly approach is far-reaching and demanding.*

*This paper explores the integration of systems and design thinking from a neurocognitive and mindset development perspective. It will also identify barriers and enablers to cognitive integration, and propose a prefatory model for integrating systems and design thinking. .*

***Keywords**: Complexity; systems design mindset; design neurocognition; systemic design; wicked problems*

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## Living in a Systemic World

Life and living become possible because of systems and the multiple interactions within and between them. Systems are intrinsic to the behaviour of all biological organisms. The unicellular, soil-dwelling amoeba continues to trigger scientific exploration for advanced techniques to address knowledge gaps in amoeba-bacteria interactions, and attempts to arrive at insights for medicine and agriculture (Shi, et al., 2021; Strassmann & Queller, 2018). What is at play here is the biologist's perspective and practice of locating the amoeba within the larger systems in which it lives and breathes. These scientists seek to understand the deeper structures, relationships, reactions, constraints and evolutionary developments, by venturing beyond the boundaries of the cellular containment of amoebae. In doing so, they inform, influence and impact other domains such as environmental science, genetics, and tissue engineering. This ability and need to identify, appreciate and understand the interconnectedness of life was exquisitely expressed by Pascal in 1670, thus:

> *Since everything then is cause and effect, dependent and supporting, mediate and immediate, and all is held together by a natural though imperceptible chain, which binds together things most distant and most different, I hold it equally impossible to know the parts without knowing the whole, and to know the whole without knowing the parts in detail. (Pascal, 2018, p.24-25).*

The inter-, multi-, and trans- disciplinary perspective[1] (Choi & Pak, 2006), which lies at the heart of biological systems thinking, is applicable in understanding societal systems that have evolved and developed over centuries, beginning with the family and evolving to community, municipality, region and nation (David, 2016). The entry of systems theory and systemic thinking in scholarly discourse is attributed to the didactic and thought leadership of Austrian biologist, Ludwig von Bertalanffy in the 1940's (Bond, Tamim, Blevins & Sockman, 2022), and was formally defined in his seminal 1968 publication, entitled, 'General systems theory: foundations, development, application' (Bertalanffy,1968).

As Bertalanffy's general systems theory (1968) evolved and developed, its concepts and principles have been incorporated and applied in a variety of disciplines and domains. Around the same time, the term 'wicked problems' began to emerge to describe the conflict, confusion and complexity that arises from problems that develop as a result of interacting factors within and between systems. Churchman's (1967) early definition of wicked problems reflects this:

> *The term 'wicked problem' refers to a class of social system problems which are ill-formulated, where the information is confusing, where there are many clients and decision makers with conflicting values, and where the ramifications in the whole system are thoroughly confusing. The adjective 'wicked' is supposed to describe the mischievous and even evil quality of these problems, where proposed 'solutions' turn out to be worse than the symptoms. (in Churchman, 1967, B-141).*

Concurrently, Horst Rittel, a budding design theorist of the 1960s, began to explore, write and dialogue about the nature of wicked problems and the role of planners, designers and decision makers in addressing them. Two decades later, Rittel’s conceptualisation of wicked problems (Rittel, 1989, in Protzen & Harris, 2010), would go on to include descriptors such as complicated, confusing, unique, unpredictable, dynamic and constantly changing. Rittel (Protzen & Harris, 2010) was emphatic that wicked problems are systemic and compounding over time, with no correct or single-solution answers.

Almost four decades later, 21st century governments, academics, and trade and industry leaders, continue to strive to understand, predict, and confront problems and seek solutions to the struggles and inequalities of a world besieged by VUCA - volatility, uncertainty, complexity and unambiguity (Gheerawo, Flory & Ivanova, 2021).

[1] Interdisciplinarity analyses, synthesises, and harmonises links between disciplines into a coordinated and coherent whole.
Multidisciplinarity draws on knowledge from different disciplines but stays within their boundaries.
Transdisciplinarity relies on different disciplines working jointly to create new conceptual, theoretical, methodological, and translational innovations that integrate and move beyond discipline-specific approaches to address a common problem. (Choi & Pak, 2006, p. 351)

## *A World of Systemic VUCA and BANI*

The VUCA concept was first used in 1987 (Giles, 2018) to describe the ambiguity and new world dynamics that began to emerge at the end of the Cold War. Many large corporations and governments have met these challenges by employing VUCA-based thinking and tools developed by academics and organisational development experts. Today VUCA-based organisational development includes leadership training, business planning, project and change management strategies, processes and operations. Baran & Woznyi (2020) maintain that agility and adaptability are key competencies underlying all VUCA response and preparedness training which includes, but is not limited to, effective emergency management, learning new technologies, being stress resistant, flexible and creative, sharing knowledge and team work, developing soft skills for managing risks in unstable situations, and digitalisation and implementation of smart tech solutions (Glukhova, Sherstobitova, Korneeva, & Krayneva, 2020). All of these competencies appear in systems thinking responses and theoretical frameworks (Giles, 2018; Protzen & Harris, 2010).

Academics and industry experts, however, continue to grapple with developing parameters against which one may assess and measure the effectiveness of the many VUCA-thinking, future-readiness and resilience programmes (Baran & Woznyi, 2020) that have pervaded the organisational development market, the aims of which are to enable organisations to successfully develop, change, grow and create products, services and solutions for the customers and stakeholders they serve. VUCA-related foresight, insight, and planning strategies are primarily geared towards anticipating, addressing and avoiding systemic, behavioural and organisational failures (Snowden & Boone, 2007). This is not always possible as evidenced by the global crises that continue to emerge from the onslaught of the Covid-19 pandemic.

A very recent and not-as-yet-in-the-academic-domain concept that has emerged, and which is gaining momentum post-Covid-19, is ‘BANI’, an acronym created by American anthropologist and futurist, Jamais Cascio (2008). Casio’s work focuses on the importance of long term, systemic thinking to help build more resilient societies and solutions.

Cascio's BANI model (2020) was first presented in 2018 at The Institute of The Future (IFTF), and has gained increasing attention and relevance since the onset and ensuing unfolding of the Covid-19 pandemic (Think Insights, retrieved May 12, 2022). This may be because it describes more closely the experience of individuals, communities, nations and governments, as they face change and new challenges unravelling in systems relating to healthcare, education, economics, environmental, and other social dynamics.

Cascio describes BANI as an intentional parallel to VUCA, and explains that volatility and complexity are now accepted as the global norm, whilst the current state of the world has moved beyond instability into the ‘age of chaos’ (Casio, 2020), a universally recognised threat of systems and systemic living. Cascio defines chaos as:

> *Situations in which conditions aren’t simply unstable, they’re chaotic. In which outcomes aren’t simply hard to foresee, they’re completely unpredictable. Or, to use the particular language of these frameworks, situations where what happens isn’t simply ambiguous, it’s incomprehensible. (Cascio, 2020).*

## *BANI: A Parallel To VUCA*

In terms of future planning and development of creative and empathic solutions for a hyper-connected world in turmoil, Casio (2020) advises to approach problems, ideas and solution-finding through a BANI assessment filter. Below is a brief description of the BANI (Casio, 2020) acronym with illustrative systemic examples:

- **Brittle:** meaning to have no or very low resilience in response to change and uncertainty; may breakdown despite being currently reliable and functional.
  Systemic examples: energy grid; global trade; healthcare provision, monoculture farming.

- **Anxiety:** meaning helplessness, chronic fear, passivity driven by fear, anticipating disaster or breakdown; fear of making wrong or poor decisions; FOMO (fear of missing out).
  Systemic examples: real or anticipated financial threat and crises, rapid pace of workplace transformation.

- **Non-linear:** meaning small decisions leading to large-scale, disproportionate consequences; a time-lag or delay between cause and effect. In some case the delay can span decades or centuries.
  Systemic examples: Covid-19 pandemic, global-warming induced climate change, terrorism as non-linear warfare.

- **Incomprehensible:** meaning hard to understand; lacking logic or purpose.
  Systemic examples: Brexit regulations, complex algorithms that can lead to unintended racist, sexist, and other biased outcomes.

A world afflicted by BANI appears rather dystopian and possibly even apocalyptic. One must, however, keep in mind that this is the real-word that presents itself to the human-centred designer who strives to envision future scenarios, and works to mitigate and eliminate risks on one hand, whilst concurrently attending to variables that enhance quality of life and user experience on the other.

Cascio (2020) does not abandon the world to its BANI characteristics. He (Casio, 2020) offers counterbalances to redress the impact and effects of living in a world of intra- and inter- connected systems (e.g. healthcare, transport, environmental). Figure 1 is a diagrammatic representation of BANI factors and their counterbalance strategies. These counterbalance strategies are useful, as they can also assist designers in their systemic cognitive and creative processing of the problems and innovations they are tasked with.

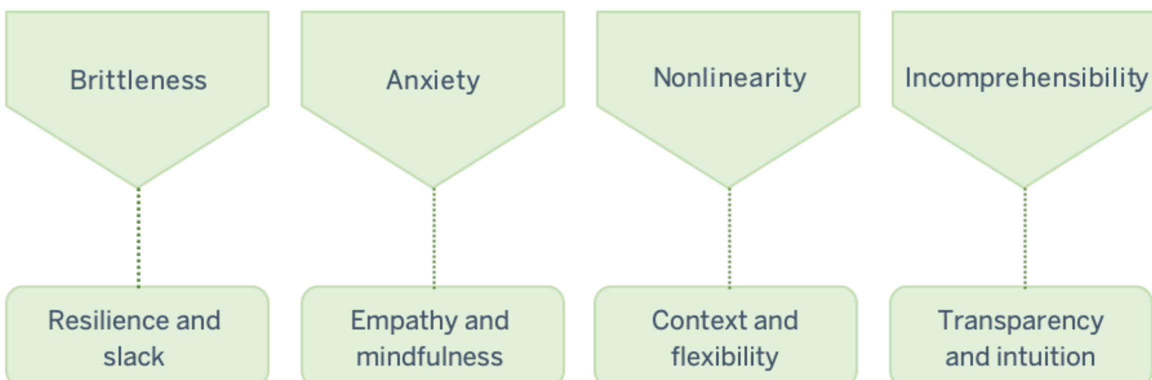


*Figure 1. BANI and Counterbalance Approaches. Source: Cascio (2020).*

## Systems Thinking for Real World Design Challenges

### *Defining Systems Thinking*

Both academic and popular literature sources are liberally populated with treatises that discuss the benefits of systems thinking. Yet, the term itself has been defined and redefined several times over since it was first coined in 1987 by American systems scientist, Barry Richmond (Richmond, 1994). Over the years it has come to mean different to things to different groups and disciplines. Systems thinking has thus alternatively been described as a philosophy, diagnostic tool, perspective building approach, systemic practice and problem solving method (Arnold & Wade, 2015; Cascio, 2020; Senge, 2008).

In an attempt to answer the question, ‘If it is so important, then what exactly is systems thinking?’, Arnold & Wade (2015) set out to methodically arrive at a new definition of systems thinking that would enable its widespread adoption across academia, industry and government. They first conducted a systematic review of the literature. They then proceeded to apply systems thinking to itself to devise a ‘systems test’ (see Figure 2), through which they distilled the key components of systems thinking in order to arrive at a singular definition (Arnold & Wade, 2015, p. 671).

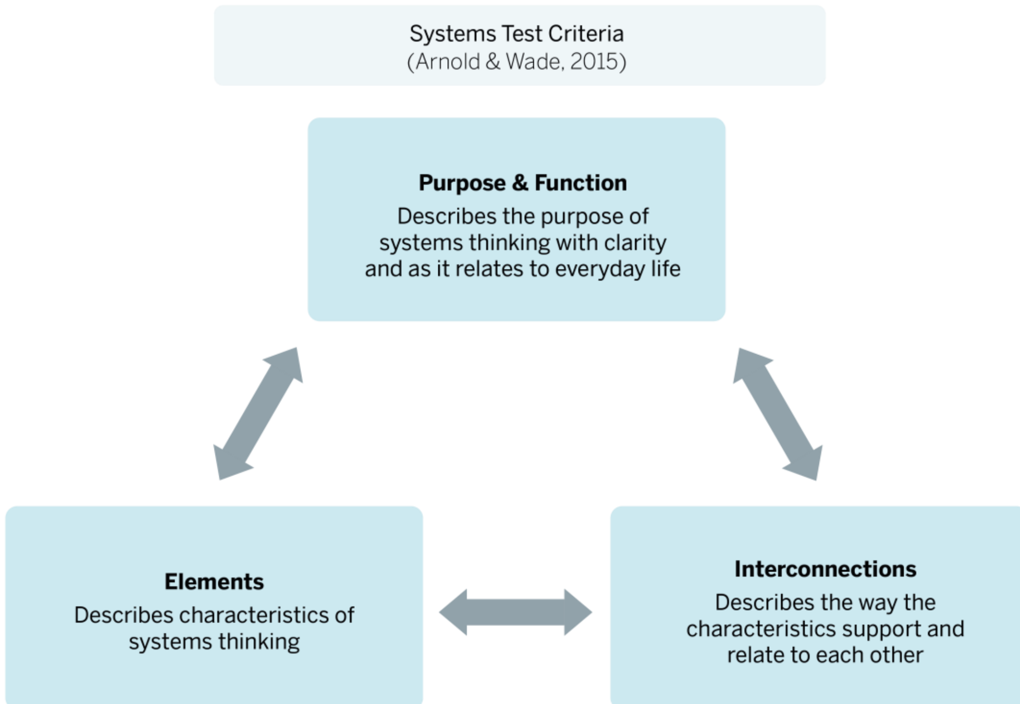


*Figure 2. Systems Test Criteria For Establishing A Systems Thinking Definition. Source: Arnold & Wade (2015, p.671)*

On completion of the systems test process, Arnold and Wade (2015) published a definition which they assert can be presented in an understandable way to a diverse audience, including those with no background in systems science:

> *Systems thinking is a set of synergistic analytic skills used to improve the capability of identifying and understanding systems, predicting their behaviors, and devising modifications to them in order to produce desired effects. These skills work together as a system. (Arnold & Wade, 2015, p.675).*

Across the globe, a growing number of scholars, researchers, practitioners and academics, are heeding the call to incorporate systems thinking in design theory and practice (Norman, 2009). Academic and design consultancies such as IDEO (2022), Design Thinkers Academy London (2022), Carnegie Mellon School of Design (2022), Rhode Island Center for Complexity (2022), Change Labs at Stanford University (2022), Centre for Systems Engineering at the University College London (2022), and the Helen Hamlyn Centre for Design at the Royal College of Art (2022), are a some of the notable institutions who have developed offerings of systems theory and thinking educational resources for academic and non-academic audiences. These range from executive education, symposia and conferences to curriculum based modules that cater to a wide range of learner interest and needs. Mayer & Norman (2020), however, submit that these efforts are still not nearly enough to move the design profession forward and into realising the value of design in the 21st century.

### *Systems Thinking For Real World Problems*

The real world depends on systems connected through complex inter- and intra- related networks that are non-linear, often unpredictable (Cabera & Cabera, 2015), dynamic, adaptive, self-preserving, operating via the flow of information through its interconnected parts, and whose interconnections if changed, can dramatically change the function and purpose of the system itself (Meadows, 2015, p. 16). A point in example is the changing nature and purpose of a healthcare system which is an amalgamation of complex adaptive systems, with intricate models of financing, complicated, complex and diverse stakeholder needs, and multiple and multilevel moving parts (Braithwaite, 2018). Since the Covid-19 outbreak, collectively, the world's health care has experienced strain and breakdown at local, national and international levels, and healthcare providers have been left unable to be a source of reliable and accurate information and to operate as usual. Medows' (2015, p.16) forewarning that 'the purpose and function of the system itself changes', has come to pass.

As early on as 1972, environmental scientist and founder of the distinguished Academy for Systems Change, Donella H. Meadows, advised that governments, organisations and individuals would have to make a major shift to the way we view the world and its systems, if we are to collectively correct and redress the 'unbalanced and dangerously deteriorating world situations' facing humanity (Meadows, 1972, p.193). These situations typically refer to Rittel's wicked problems (Protzen & Harris, 2010), and include real-world systemic challenges and crises in the social, economic, environmental, humanitarian, political, technological , and governance domains of policy, practice and provision (Carbera & Carbera, 2015; da Costa, Diehl & Snelders, 2019).

Design has a critical role to play in heeding this cry. Designers have the capacity to transcend silos and sectors (Design Council, 2021, p.6). Designers come from a variety of professional backgrounds and knowledge domains spanning the arts, humanities, and STEM disciplines, and work competently in multi-, and inter-disciplinary teams. Designers are trained to work collaboratively, listen empathically, envision, propose, create and re-purpose products, services, and policies in ways that transcend the limitations of reductionist and analytical thinking.

The major premise of this paper relates to the proposal for an integration of design and systems thinking - which in themselves incorporate multidisciplinary thinking - to engage with challenges 'characterised by complexity, uniqueness, value conflict, and ambiguity' (Ryan, 2014, p.1), over fixed goals and objectives. This synthesising approach is recognised as the distinct emerging field of systemic design or systems design approach (Duman & Timur, 2019; Ryan, 2014).

For the purpose of this paper, the author subscribes to Arnold and Wade's (2015) definition of systems thinking presented earlier, wherein the application of a set of synergistic analytical skills is used to improve identification and understanding of the system[s], as a precursor to innovating solutions with desired effects. Heeding Ryan's (2014) advice to avoid subscribing to any one dominant school of design thinking, and instead, to relate in general terms to the overarching concepts of design, affords the necessary flexibility for smooth integration of design and systems thinking. Accordingly, Ryan's definition serves well: 'By design thinking, we mean a normative, user-centred, iterative approach to innovation that extends the application of design beyond the design of symbols, objects, and interactions.' (Ryan, 2014, p. 3).

### *Towards Systemic Design or A Systems Design Approach*[2]

So what is a systems design approach? Starting with the common ground of multidisciplinarity of theory and praxis which are the very foundations of these two disciplines, Ryan (2015) posits that a methodical and mutual integration of systems and design perspectives will result in the increased capacity for designers to understand situations from multiple perspectives and scales, challenge boundaries and construct new shared frames of reference. This proposed uptake of cognitive integration (Choi & Pak, 2006) between systems and design thinking, would in turn, lead to the cross-cognitive competency of systemic design thinking. Ryan (2015) further claims that filtering complex problems through a systems thinking lens would result in enhanced capacity for visualising paradigm shifts, whilst encouraging reflective thinking and learning whilst doing. Systemic design 'provides ways of deeply empathising with stakeholders, while working alongside them to collectively apprehend and construct a broader context within which to situate our challenges.' (Ryan, 2015, p. 3).

Whilst there is much to be done to equip designers of the future with specific systemic design skills and mindset, it is also fair to note that some aspects of design education, research and practice already seek the incorporation of specific systems thinking competencies through intent and praxis. Two cases in point, but beyond the remit of this paper, are the continually developing fields of inclusive design (Coleman, 1994) ) where the principal focus is on human-centred inclusion through immediate and longer-term considerations such as accessibility, usability, community, and quality of life; and sustainable design (Keitch, 2012) which, in a nutshell, seeks to integrate human-centredness with planet-mindedness.

[2] The author uses the terms, 'systems design approach' and 'systemic design' interchangeably to mean the incorporation and integration of a system thinking lens in designerly thinking, theory and praxis.

Sevaldson (2013, p. 1765) succinctly concludes of design, 'There already exists practices geared towards dealing with complexity. But such practices need to be systematized and developed further.'

## The Systems Design Mindset: A Neurocognitive Perspective

The terms systemic design and design thinking have attracted much attention and debate over the last decade or so. This paper presents the cognitive competencies and neural correlates identified by neuroscientists and psychologists whose research endeavours aim to explore and understand the thinking strategies employed by designers tasked with complex societal, technological, environmental and other wicked problems. A noteworthy outcome of the evidence based knowledge emerging from these studies, is the ongoing development of what a systemic design mindset entails, and what the teachable and learnable cognitive and behavioural competencies of systemic design thinking are.

Cognitive neuroscience is a branch of neuroscience that seeks to use observations from the study of the brain to help unravel the mechanisms of the mind (McClelland, 2001, p. 2133). In recent years, cognitive neuroscience research has entered the world of workplace behaviours and experience, and has begun to produce meaningful measurements, assessments and applications for occupational science (Williams & Lewis, 2020). The growing body of well-established findings in cognitive psychology and neuroscience research in real-world, ecologically-valid, educational and professional settings, is important for developing new methods and tools for performing and teaching design (Chrysikou & Gero, 2020; Kannengiesser & Gero, 2019).

Design thinking involves processing of complex cognitive content via neural networks that interact across the entire brain. Design is ubiquitous (Simon, 2019) and designing, according to Chrysikous & Gero (2020, p. 319), is the 'cognitive act of intentionally generating new ways to change the world instead of simply repeating existing ways.' From a neuroscience perspective, designerly thinking corresponds to neurocognitive processes in the brain that support the designer in conceiving new ideas and concepts, and developing them further through several cycles of iterative testing and design. The study of cognitive brain activation to advance understanding and knowledge of designerly cognition has led to the burgeoning field of design neurocognition[3] (Flory & Ivanova, 2019; Gero & Milovanovic, 2020; Vieira, Gero, Delmoral, Parente, Fernandes, et al., 2019).

What is remarkable about the emerging design neurocognitive studies is that these research scientists are seeking to interpret their findings in the context of design theory (Greene & Papalambros, 2016). This is important because the insights arrived at can inform help co-create new opportunities for design education and professional development of students and designers, and provide pathways to developing, integrating and applying systems thinking to specific complex problems and tasks (Basset & Sporns, 2017). In describing the primary intent of design neurocognition research, Gero & Milanovic (2020) state:

> *The foundational goal of design research is to gain a better understanding of designing in order to improve the design process, to produce tools for designers, to improve design pedagogy, and consequentially to improve the outcome of designing. (Gero & Milanovic, 2020, p. 10).*[4]

A majority of the neurocognitive research in systems thinking and systemic design problem solving has been in the domain of systems engineering, a discipline vastly different from design in its knowledge and educational underpinnings. Scientists at NASA maintain, however, that the cognitive skills and designerly behaviours of systems engineers is not very dissimilar to that of other designers. This perspective is substantiated in NASA's definition of systems engineering as an art and science that deals with real-world complex problems through multidisciplinary team collaboration.

> *Systems engineering is a holistic, integrative discipline, wherein the contributions of structural engineers, electrical engineers, mechanism designers, power engineers, human factors engineers,*

[3] Tracing and measuring brain activation during designing activities is accomplished through methods such as functional magnetic resonance imaging (fMRI), function near-infrared spectroscopy (fNIRS), and electroencephalography (EEG). These non-invasive approaches help researchers to understand the specific cognitive processes of designers as they engage in designing activities.

[4] Gero & Milanovic (2020) are referring here to the functional goal of neuroscience-based design research to advance the understanding of design thinking, which they maintain can only be achieved through in-vivo examination of neurocognitive processes taking place whilst designers work on real-world design problems.

*and many more disciplines are evaluated and balanced, one against another, to produce a coherent whole that is not dominated by the perspective of a single discipline. (NASA, 2019).*

Furthermore, the work of Professor Moti Frank, an award winning systems engineer, researcher and thought leader in the field, which he describes as 'systemic thinking in systems engineering' (Frank, 2006, p. 91), has progressively demonstrated a positive correlation between the capacity for systems thinking and successful design of large scale, complex systems and systemic design solutions. The following section describes the neurocognitive findings from studies that have included participants from across a wide range of design science disciplines.

### *Design Neurocognition and Systemic Design Thinking: In-vivo Research*

Design neurocognitive research makes a study of the neurological processes that occur during acts of designing. Going beyond the observational methods of behavioural psychology, design neurocognition research arrives at evidence and insights based on the scientific method of controlled experiments and in-situ (i.e. studio-based) studies, in which designing is treated as a series of cognitive process.

A recent study of brain behaviour (Hu, Shealy & Milanovic, 2021) compared brain activation between first year and senior engineering students when generating design solutions with and without the additional dimension of complex sustainability related design challenges. The study showed significant differences between the two groups. Senior students engaged more with self-reflection in their solutions finding and in the processing of the uncertainty elements which were embedded in the complexity based (sustainability) design tasks. First-year students, on the other hand, showed activation of brain areas involved in working memory and abstract reasoning. These findings are important. They tell the story of designerly development and progressive attainment of cognitive skills and abilities over time.

Working memory is categorised as a complex cognition (Miyake & Shah, 1999) and refers to the mental processes relating to human reasoning, problem solving and decision making (Mann, 2016). Abstract thinking or abstract reasoning refers to thinking related to concepts, principles, and relationships between ideas and objects (Knauff & Wolf, 2010).

Over and above these cognitive competencies, consider the self-reflection recorded of the senior student group when faced with the complex sustainability design tasks. Self-reflection is a form of meta-cognition (see footnote 9) and an adaptive-based cognitive ability to look at specific behaviours and experiences and develop new learning and insights from them (Knapp, Gottleib & Handlesman, 2017). Knapp et al., (2017) maintain that self-reflection enhances professional development through increased ability to make self-directed changes to one's own attitudes and behaviours. They (Knapp et al., 2017) argue that self-reflective cognition doesn't happen automatically or spontaneously. Instead, it is a cognitive skill that is nurtured over time, and through ongoing education and experiential learning.

It is reasonable to conclude from this that design education has an impact on design thinking, progressively training students to develop thinking from problem assessment and solution finding in the initial years, to self-reflective evaluation of the impact of the decisions and solutions they think about. This cognitive skill is directly transferable and relevant to the systemic design mindset.

In another study, Hu et al., (2021) found that when they included dimensions of sustainability in the design task, the number of solutions generated by first-year engineering students reduced, whilst the senior engineering group continued to generate as many, or even more creative ideas. The positive correlation seen here reveals that progressive educational development in design, increases ideation and creative cognition abilities such as creative brainstorming, concept generation and the number of novel ideas.

In another study, an international multidisciplinary research team which included medicine, architecture, engineering and technology, set out to determine if there were brain activation differences between problem-solving and designing activities (Vieira, Gero, Delmoral, Parente, Fernandes, Gattol, & Fernandes, 2019). The study used EEG[5] to measure and compare brain activation differences between mechanical engineers and architects whilst they participated in a series of systemic design exercises. Additionally, the experiment consisted of multiple tasks which differentiated between day-to-day problem solving cognition, and design-related cognitive processing such as idea generation, creative brainstorming, concept reframing, concept generation, pattern recognition and comparative thinking

[5] An electroencephalogram (EEG) is a painless test that detects tiny electrical charges in the brain using small, metal discs called (electrodes) attached to the scalp. The charges are amplified and appear as a graph on a computer screen which can then be interpreted by a researcher or clinician. An EEG procedure is usually carried out by a highly trained specialist such as a clinical neurophysiologist.

amongst others. Statistical analysis of the data indicated increased activation when performing designerly tasks and thinking compared to problem-solving in both groups. The authors concluded that design thinking and systems-based thinking in design is a learned cognitive skill and can be distinguished from problem solving.

In a subsequent study the following year, this international group of researchers (Vieira, Gero, Delmoral, Gattol, Fernandes, Parente & Fernandes, 2020) carried out yet another EEG study to measure differences in brain activity, this time between mechanical and industrial engineers who were presented with a series of problem solving and complex design tasks. Consistent with previous findings (Vieira et al., 2019), the 2020 study revealed significant differences in neural activation between problem solving and designerly thinking. The researchers concluded that the neurophysiological results arising from 18 experiment sessions in this round of research, revealed that the higher alpha, beta and theta brain wave frequencies recorded in both groups conclusively distinguish design and complex design thinking from problem solving.

### *The Increasing Need For Systemic Design Thinking*

Meyer & Norman (2020) believe that designerly ways of thinking and doing which are distinct from problem solving and problem mitigation skills, are in increasing demand in today's world of complex systems interaction and impact. They succinctly express their view thus:

> *Meanwhile, skills for developing creative solutions to complex problems are increasingly essential. Organizations are starting to recognize that designers bring something special to this type of work, a rational belief based upon numerous studies that link commercial success to a design-driven approach. (Meyer & Norman, 2020, p. 13).*

The relevance of citing the emerging evidence based insights in the burgeoning field of design neurocognition in the previous section, is to demonstrate its application across a range of design-led disciplines in which designerly and systemic thinking are employed in iterative phases of co-creative design and design research. Professor John Gero, a world-renowned researcher in the fields of design theory and design neurocognition, maintains that there are common cognitive behaviours in designing across multiple disciplines (Alexiou, Zamenopoulos & Gilbert, 2011) ranging from architecture and engineering to software and user experience design (Gero & Milanovic, 2020), all of which involve systemic thinking to a more or lesser degree. ‘This has the potential to have a profound impact on design education if designing has a common core of cognitive behaviors.’ (Gero, Kannengiesser & Williams, 2014, p.6). In a systemic world of VUCA and BANI, the possibility of co-creating generic design education modules for multidisciplinary designer cohorts, whilst challenging, would afford a real-world and rich learning experience for design-thinking students and professionals.

## Integrating Systems And Design Thinking For 21st Century Design and Innovation

### *Beyond Problem Solving: Cognitive Competencies of Systemic Design Thinking*

Successful systems and design thinking are both heavily reliant on higher-order cognitive skills and a clear understanding of why, when and how to utilise them (Greene & Papalambros, 2016). Higher-order thinking includes cognitive competencies such as:

- executive function [6]
- analogy
- problem solving
- decision making
- causal reasoning

[6] Executive functions are cognitive process necessary for self-regulation of emotion and behaviour, and goal directed behaviours. The mental processes of executive functions enable one to plan, focus attention, remember instructions, and juggle multiple tasks successfully. Executive function also includes initiation, mental flexibility, novel problem solving, planning, and self-awareness.

- spatial reasoning
- transfer [7]
- categorisation [8]
- contextually-relevant creative problem solving (e.g. sustainability)
- motivation
- metacognition [9]

(Eysenck & Keane, 2020; Mann, 2016).

Notable contributions to the burgeoning field of design neurocognition stem from researchers and thought leaders in the fields of cognitive neuroscience (Chrysikou et al., 2019; Gero & Milanovic, 2020), education (Duman & Ogut, 2019; Ryan, 2014; Voûte et al, 2020), engineering, technology and computer science (Frank 2000; Frank 2006; Frank 2012; Greene & Papalambros, 2016), design science, and cognitive psychology (da Costa et al, 2019; Hu et al, 2020; Vieira et al, 2020). Professor Moti Frank, with his perspective-leading, progressive research history in systems thinking, maintains, 'To successfully perform their tasks, systems engineers need a systems view.' (Frank, 2006, p. 91). This premise could equally be applied to designers who address complex, wicked problems, or whose design remit includes contextual VUCA and BANI conditions. This view is supported by Gero et al., (2014), who attest to empirical evidence for the need to co-develop a systemic design curriculum wherein systems-based cognitive competencies (Visser, 2009) for addressing wicked and complex problems, are taught and learned across the majority of design-related disciplines (Cross, 1982), irrespective of their theoretical underpinnings, praxis and research methodologies.

### *Cross-Mapping Systems Design Cognition and Cognitive Processes*

What would these systemic design cognitive competencies look like? Greene & Papalambros (2106) have made a detailed, critical evaluation of Frank's (2000, 2006, 2012) CEST Competency Model (Capacity For Engineering Systems Thinking) which identifies 16 cognitive competencies, 9 skills/abilities, 7 behavioural competencies, and 3 knowledge and experience factors of successful systems engineers.

In relation to the cognitive competencies, which is the focus of this paper, Greene & Papalambros (2016, p. 4) assert, 'Frank's work offers a solid foundation for developing a cognitive approach to [systemic design] systems thinking.' Greene & Papalambros (2016) posit that the 16 CEST cognitive competencies (Frank, 2012) are descriptions of 'design doing' rather than cognitive competencies, as defined in the domains of cognitive psychology and neuroscience. Whilst this is a fair critique and indeed helpful, a plausible counter argument is that the use of the word 'understanding' that precedes Frank's (2016) competency descriptors and the meaning they convey, could very well represent a cognitive competency called fluid cognitive ability which psychologists define as the capacity to process and integrate information, think abstractly, act, and solve novel problems (Baltes, Staudinger & Lindenberger, 1999; Carroll, 1993), which can be distinguished and developed beyond general intelligence (Blair, 2006).

Whichever view one takes, Greene & Papalambros' interpretation (2016) has had the positive and desired effect of going beyond Frank's CEST model (2012), to identify and clearly describe specific systemic design cognitive components required for our increasingly interconnected world of systemic living. Greene & Papalambros (2016) have supplemented the CEST model (Frank, 2012) to elevated potential and application for future development in design theory, education and research, by augmenting each of Frank's (2012) cognitive descriptors with specific cognitive processes and skills drawn from cognitive psychology and neuroscience, which they deem are necessary for systemic designerly thinking and praxis. A reproduction of their (Greene & Papalambros, 2016) cognitive mapping exercise appears in Figure 3.

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[7] Transfer refers to the ability to apply knowledge and skills to new contexts.

[8] Categorisation refers to the ability to analyse and evaluate complex information, make connections and categorise the information.

[9] Metacognition refers to the knowledge and regulation of one's own thinking processes, which is considers a critical component of creative thinking.

Table 1: Mapping between cognitive competencies of systems engineers and cognitive processes required for generating these behaviors.

| **Frank's cognitive competencies [1]** | **Cognitive psychology related concepts [20-25]** |
|---|---|
| *Understand the whole system and see the big picture* | Sensemaking; information integration; mental model formation; generalization |
| *Understand interconnections* | Induction; classification; similarity; information integration |
| *Understand system synergy* | Deductive inference |
| *Understand the system from multiple perspectives* | Perspective taking (direct mapping) |
| *Think creatively* | Creativity (direct mapping) |
| *Understand systems without getting stuck on details* | Abstraction; subsumption |
| *Understand the implications of proposed change* | Hypothetical thinking |
| *Understand a new system/concept immediately upon presentation* | Categorization; conceptual learning; inductive learning/inference |
| *Understand analogies and parallelism between systems* | Analogical thinking (direct mapping) |
| *Understand limits to growth* | Information integration |
| *Ask good (the right) questions* | Critical thinking |
| *(Are) innovators, originators, promoters, initiators, curious* | Inquisitive thinking |
| *Are able to define boundaries* | Functional decomposition |
| *Are able to take into consideration non-engineering factors* | Conceptual combination |
| *Are able to "see" the future* | Prospection |
| *Are able to optimize* | Logical decision-making |

*Figure 3. Mapping between cognitive competencies of systems thinking (Frank, 2012) and cognitive processes required for generating these behaviours (Greene & Papalambros, 2016). Reprinted by permission from Greene & Papalambros (2016, Table 1, p. 5).*

An in-depth discussion regarding the value and application of each of the cognitive competencies laid out by Frank (2012) and Greene & Papalambros (2016) is beyond the scope of this paper. The value of the clarification that issues forth from this cross-mapping exercise, however, has immensely important implications in shaping future developments for systemic design thinking, theory, research and practice. 'In a sense, a shift from using engineering terminology to describe cognitive phenomena to using cognitive terms to describe cognitive phenomena' (Greene & Papalambros 2016, p. 5), is the necessary precursor to including cognitive psychologists and neuroscientists alongside designers and design educators, to co-creatively refine and evolve design thinking, theory and programmes for acquiring and mastering these systemic cognitive skills. Evidence based methods from educational-, cognitive- and neuro- psychology, would be of immense support in achieving the goal of improving and instilling systems thinking and multidisciplinary collaboration in the designer mindset.

This cross-mapping model of cognitive competencies for systemic design thinking (Frank, 2012; Greene & Papalambros, 2016) has come full circle. It attends to and fulfils Arnold & Wade's (2015) methodical application of systems thinking to itself to identifying the key cognitive competencies of systemic design thinking. The thoroughness of this mapping has aided psychologists and neuroscientists in developing research hypothesis and experiment conditions aimed at understanding systemic designerly thinking and application across a range of design-based disciplines. Learning and insights from these studies have begun to inform the education and continuing professional development of systems engineers (Chrysikou & Gero, 2020; Gero, Kannengeisser & Williams 2014; Gero & Milanovic, 2020).

### *Integrating Systems and Design Thinking: A Prefatory Model*

Building on this evidence, Figure 4 proposes a prefatory model of how this approach - applying systems thinking to integrating systems and design thinking for designers - might be adopted to shape and develop theory, research, education and practice of inclusive design, thereby enabling designers to successfully co-design and innovate in response to wicked problems and systemic dilemmas.

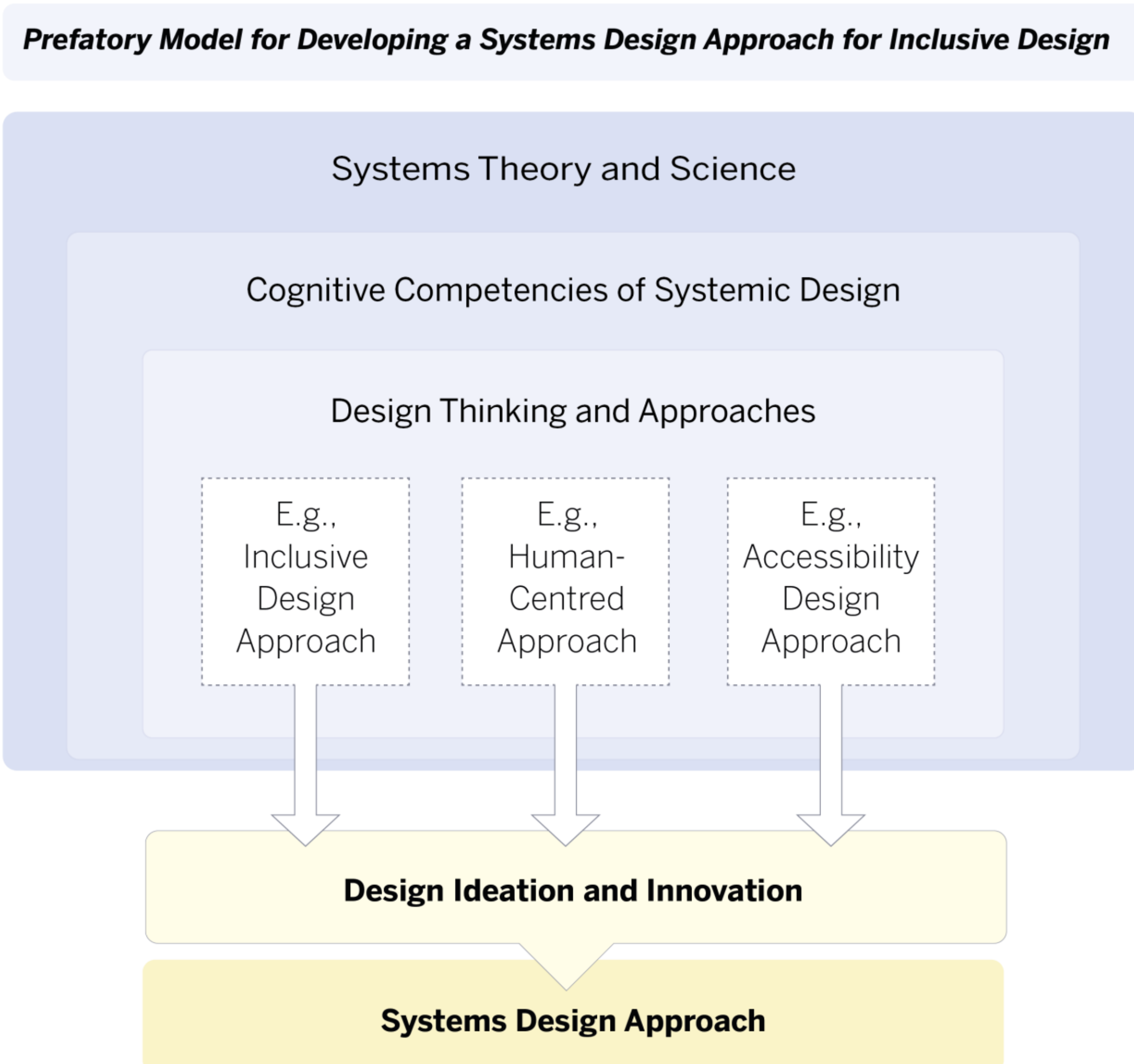


*Figure 4: Prefatory Model for Developing a Systems Design Approach for Inclusive Design*

Despite the myriad of systems thinking definitions in existence, if we accept that systems thinking is a way of seeing, talking and thinking about systems and their complex interrelationships with other systems (e.g., healthcare), it becomes apparent that developing systems thinking capabilities is desirable for designers and design domains. This prefatory model serves as a preamble to stimulate deliberation and discourse amongst design communities regarding the need, benefits, limitations, opportunities and challenges of embracing and incorporating systems thinking in their designerly consideration of complex and wicked problems.

Every day we are besieged with the evidence of insoluble wicked problems such as hunger, obesity, poverty and terrorism, precisely because these problems are not self-contained and easily defined. Additionally, complex and wicked problems do not sit neatly interconnected within and between the systems that impact upon them, and upon which they in turn, create impact. There are too many moving, unknown and emerging parts, and numerous unseen and unrecognised stakeholders, all of which threaten and challenge successful designerly innovation and creative solution finding.

Dorst (2019) maintains that if design is entering a time of true complexity, then for design to reach its full potential in creating change and strategic transformation (Watson & Kees, 2020), '... we have to radically shift our thinking and move away from design paradigms based on problem solving.' (Dorst, 2019, p. 122). The fledgling model presented in Figure 4 can provide the foundation to help us move beyond problem solving. At a minimum, it maps out the cognitive domains and layers to be journeyed in facing Dorst's 'truly complex' problems (Dorst, 2019, 122).

## Conclusion

The purpose of this paper is to explore the possibility of integrating the cognitive competencies of systems and design thinking in designerly praxis. Seeking to understand the systemic design mindset, it draws heavily on design neurocognitive research related to the systemic thinking behaviours of engineers, architects, designers, mathematicians, clinicians and design students. An overarching finding across all these disciplines shows that intelligent utilisation (i.e. understanding of why, when and how) of higher-order cognitive skills (Greene & Papalambros, 2016), is essential to being able to apply systems-based design thinking to address and creatively develop solutions, alternative scenarios and early prototypes.

Recent well thought through research studies emanating from the budding discipline of design neuroscience together with their ensuing findings (Frank, 2000; Frank, 2006; Frank, 2012; Gero & Milanovic, 2020; Hu et al., 2021; Vieira et al., 2020; Visser, 2009), have begun to provide a promisingly robust and cohesive basis for understanding the specific systems cognitive skills that designers across a range of design disciplines successfully utilise to tackle real world complex problems. Whilst these findings relate to experimental and controlled conditions, they nevertheless offer foundational beginnings into understanding the cognitive complexities involved in addressing systemic design and innovation tasks.

This new field of research will inevitably impact and inform future developments in design theory, research, education and continuing professional development of designers, even more so as we are at a time when 'organizations are starting to recognize that designers bring something special' (Meyer & Norman, 2019) to the work of developing creative solutions to complex problems.

Of particular relevance, is the fact that many of these recent studies exploring systemic design cognition and brain behaviour have been carried out in multiple project locations across the globe, including Australia, Croatia, France, Italy, Sweden, Switzerland and the USA (Hay et al., 2020). Of the many relevant insights derived from the data, specific attention is drawn to the following three because of their direct relevance to the theme of this paper, which posits the integration of systems and design thinking in theory, education and practice.

### *Insight 1:*

Systems thinking is comprised of specific cognitive components that are detectable and measurable via neural processing networks. These cognitive capacities are applied by designers across the majority of design domains in situations where systems thinking is necessary for addressing complex real-world societal and technological questions, challenges, and calls for innovation (da Costa et al., 2019; Frank, 2012; Greene and Papalambros, 2106; Meyer & Norman, 2020).

### *Insight 2:*

There is a significant difference between first-year design students and senior students (years, 3, 4, 5) in applying systems view cognition. Senior students apply a greater number and variety of higher-order types of cognition more frequently (e.g. categorisation, analogy, metacognition), and with greater contextual relevance to the systemic issues within which the problem is situated, than do first-year students (Hu et al., 2021).

### *Insight 3:*

The cross-mapping of systems cognition competencies offered by Frank (2012) and Greene & Papalambros (2016), and their contextual applications by designers in systemic designing situations, can be differentiated from the application of the problem solving skills and techniques used by people in everyday organisational and life situations.

These insights are encouraging and relevant to the challenge, of 'how the design thinking community can learn from the systems thinking community and vice versa.' (Pourdehnad, Wexler & Wilson, 2011, p.13). Pourdehnad et al., (2011, p.16) state, 'We believe that systems thinking should be intentionally integrated with design thinking to enhance the chances of creating the right designs.'

In planning for a design future wherein designers will be co-developers and co-creators in systems related design, ideation, innovation and solution finding, Voûte et al. (2019) propose that one of the next steps for design research and academic institutions, is to lead the way through developing education programmes that push the boundaries of interdisciplinary and inter-sectoral collaboration, thereby, ‘connecting design researchers and design education across the world, and rehearsing new design competencies.’ (Voûte et al.,2019, p.64). The preparatory model (Figure 4) can serve to provoke critical thinking about how to go about this.

Design has its own unique history, lineage of thought leadership, and continuously developing portfolio of tools, strategies and techniques, all of which are shaped by the context of world and times we live in. It has evolved ‘from craft to sophisticated professional practice and academic discipline.' (Dorst, 2019, p. 118). Twenty-first century systemic-based living implicitly implores design to heed the need for adapting and changing to stay in tune with its new role brought about by 'extreme complexity' (Dorst, 2019, p.119).

For Norman (2106) there exists two critical parts to the field of design - design as a craft and design as a way of thinking applied to complex sociotechnical systems. Each results in relatively different outcomes and value to the world we live in. Individuals will make the choice to take either one of the paths, or they may opt to take both. Whatever the preference, Norman advises, ‘the correct answer is ... take it', because '…we need people who take each path - whichever direction any individual takes will be correct - but all should develop an appreciation for and understanding of both paths.' (Norman, 2016, p. 346).

This paper leans into the inescapable future development of design thinking for extreme complexity. The cross-mapping of cognitive competencies as intellectual capacities translated into behaviours, proposed by Greene and Papalambros (2016), the newly emerging field and research endeavours of design neurocognition, and the prefatory model represented in Figure 4, are humble beginnings on this road. I do not pretend that the prefatory model is complete, but rather it identifies the salient cognitive domains - each containing a diversity of approaches within themselves in response to their historical, philosophical and cognitive underpinnings - for consideration, discourse and debate in moving toward systemic design thinking.

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## References

Alexiou, K., Zamenopoulos, T., & Gilbert, S. (2011). Imaging the designing brain: A neurocognitive exploration of design thinking. In J. Gero, (ed.) *Design Computing and Cognition:* Proceedings of the Fourth International Conference on Design Computing and Cognition, Stuttgart, Germany (pp. 489–504). London: Springer.

Arnold, R.D., & Wade, J. P. (2015). A definition of systems thinking: A systems approach. 2015 Conference on Systems Engineering Research. *Procedia Computer Science, 44*, 669–678.

Baltes, P.B., Staudinger, U.M., & Lindenberger, U. (1999). Lifespan psychology: Theory and application to intellectual functioning. *Annual Review of Psychology, 50*, 471–507.

Baran, B.E., & Woznyj, H.M. ( (2021). Managing VUCA: The human dynamics of agility. *Organizational Dynamics, 50*(2), 1-11. doi: 10.1016/j.orgdyn.2020.100787.

Bassett, D., & Sporns, O. (2017). Network neuroscience. *Nature Neuroscience, 20*(3), 353–364.

Bertalanffy, L.V. (1968). *General systems theory: Foundations, development, application.* New York: George Baziller Inc.

Blair, C. (2006). How similar are fluid cognition and general intelligence? A developmental neuroscience perspective on fluid cognition as an aspect of human cognitive ability. *Behavioral and Brain Sciences, 29*, 109-160.

Bond, M.A., Tamim, S.R., Blevins, S.J., & Sockman, B.R. (2022). *Systems thinking for instructional designers: Catalyzing organizational change.* New York: Routledge.

Braithwaite, J. (2018). Changing how we think about healthcare improvement. *BMJ (Online), 361*, 1-4. https://doi.org/10.1136/bmj.k2014.

Buchanan, R. (1992). Wicked problems in design thinking. *Design Issues,8* (2), Spring 1992, 5-21.

Carbera, D., & Carbera, L. (2015). *Systems thinking made simple: New hope for solving wicked problems* (2nd ed.). USA: Plectica Publishing.

Carnegie Mellon School of Design. (2019). Students Release Booklet on Introduction to systems thinking. Retrieved from https://design.cmu.edu/content/students-release-booklet-introduction-systems-thinking.

Carroll, J.B. (1993). *Human cognitive abilities: A survey of factor-analytic studies.* Cambridge, MA: Cambridge University Press.
Cascio, A.M.J. (2008, March 10). SXSW: Futurist Jamais Cascio Sees GOP Filters, Alt Energy. *Wired.* Retrieved from https://www.wired.com/2008/03/sxsw-futurist-j/.
Cascio, A.M.J. (2020, April 29). Facing the age of chaos [Blog post]. Retrieved from https://medium.com/@cascio/facing-the-age-of-chaos-b00687b1f51d.
Choi, B.C.K, & Pak, A.W.P. (2006). Multidisciplinarity, interdisciplinarity and transdisciplinarity in health research, services, education and policy: Definitions, objectives, and evidence of effectiveness. *Clinical Investigative Medicine, 29 (6)*, 351-364
Churchman, C. W. (1967). Wicked problems. *Management Science, 14*(4), 141-142.
Chrysikou, E.G., & Gero, J.S.. (2020). Using neuroscience techniques to understand and improve design cognition. *AIMS Neuroscience, 7*(3), 319-326. doi: 10.3934/Neuroscience.2020018.
Coleman, R. (1994). *The Case for Inclusive Design – An Overview.* Paper presented at the 12th Triennial Congress, International Ergonomics Association and the Human Factors Association of Canada.
Cross, N. (1982). Designerly ways of knowing*.* *Design Studies, (3)*, 221-227.
da Costa Junior, J., Diehl, J., & Snelders, D. (2019). A framework for a systems design approach to complex societal problems. *Design Science, 5*(2), 1-32. Retrieved from https://doi.org/10.1017/dsj.2018.16.
David, E.J. (2012). *Social Systems, Social Lives: Introduction to Sociology.* U.S.: Kendall/Hunt Publishing Co.
Design Council. (2021). *Beyond net zero: A systemic design approach.* London: Design Council. Retrieved from https://www.designcouncil.org.uk/sites/default/files/asset/document/Beyond%20Net%20Zero%20-%20A%20Systemic%20Design%20Approach.pdf.
Design Thinkers Academy London. (2022). Systems thinking: Advanced practitioners course. Retrieved from https://www.designthinkersacademy.co.uk/courses/systems-thinking/.
Dorst, K., & Watson, R. (2020) Reframing and strategic transformation. *Proceedings of The Design Research Society, 5,* 1964-1976. https://doi.org/10.21606/drs.2020.130
Duman, S., & Öğüt, Ş.T. (2019). Competency domains for systemic design education. In N. Börekçi, D. Koçyıldırım, F. Korkut, F. & D. Jones (Eds.) *Insider Knowledge: Proceedings of the Design Research Society Learn X Design Conference, Ankara, Turkey, 9-12 July 2019.* https://doi.org/10.21606/learnxdesign.2019.13077.
Eysenck, M.W., & Keane, M.T. (2020). *Cognitive psychology: a student's handbook* (8th ed). Milton Park: Oxon.
Flory, M., & Ivanova, N. (2019). Future directions: Design meets neuroscience. *dmi:Review, 3(2),* 22-29. https://doi.org/10.1111/drev.12177.
Frank, M. (2000). Engineering systems thinking and systems thinking. *Journal of Systems Engineering, 3*(3), 163-168.
Frank, M. (2006). Knowledge, abilities, cognitive characteristics and behavioral competencies of engineers with high capacity for engineering systems thinking (CEST). *Journal of Systems Engineering, 9*(2), 91-103.
Frank, M. (2012). Engineering systems thinking: Cognitive competencies of successful systems engineers. *Procedia Computer Science, 8*, 273-278.
Frausel, R. R., Silvey, C., Freeman, C., Dowling, N., Richland, L. E., Levine, S. C., Raudenbush, S., & Goldin-Meadow, S. (2020). The origins of higher-order thinking lie in children's spontaneous talk across the pre-school years. *Cognition*, *200*, 104274. https://doi.org/10.1016/j.cognition.2020.104274
Gero, J.S., & Milovanovic, J. (2020). A framework for studying design thinking through measuring designers' minds, bodies and brains. *Design Science, 6*(19), 1-40.
Gero, J.S., Kannengeisser, U., & Williams, C.B. (2014) *Does designing have a common cognitive behavior independent of domain and task: A meta-analysis of design protocols.* Paper presented at the International Conference on Human Behaviour in Design, Ascona, Switzerland, 14-17 Oct 2014, 1-7.
Gheerawo, R., Flory, M., & Ivanova, N. (2020). Creative Leadership: Design Meets Neuroscience to Transform Leadership. *Design Management Journal, 15*(1), 102-117. http://dx.doi.org/10.1111/dmj.12063.
Giles, S. (2018, May 9). How VUCA Is reshaping The Business Environment, And What It Means For Innovation. *Forbes.* Retrieved from https://www.forbes.com/sites/sunniegiles/2018/05/09/how-vuca-is-reshaping-the-business-environment-and-what-it-means-for-innovation/?sh=642dd463eb8d.

Glukhova, L.V., Sherstobitova, A.A., Korneeva, E.N., & Krayneva, R.K. (2020). VUCA-Managers training for Smart Systems: Innovative and Organizational Approach. In V. Uskov, R. Howlett, & L. Jain (Eds.) *Smart Education and e-Learning* (pp. 361-370). Singapore: Springer.
Greene, M.T., & Papalambros, P.Y. (2016). *A cognitive framework for engineering systems thinking.* Paper presented at the 14th Annual Conference on Systems Engineering Research, Huntsville, AL, 22-23 March, 2016.
Greene, M.T., Gonzalez, R., Papalambros, P.Y., & McGowan, A. (2017). *Design thinking vs. systems thinking for engineering design: What's the difference?* Manuscript for the 21st Annual International Conference on Engineering Design, The University of British Columbia, 21-25 August 2017.
Hay, L., Cash, P., & McKilligan, S. (2020). The future of design cognition analysis. *Design Science, 6*(20), 1-26. doi:10.1017/dsj.2020.20.
Helen Hamlyn Centre for Design, Royal College of Art. (2022). *Design.Wicked: A Design-led Approach to Tackling Wicked Problems.* [Webinar]. Retrieved from https://www.rca.ac.uk/news-and-events/events/designwicked-design-led-approach-tackling-wicked-problems/.
Hu, M., Shealy, T., & Milovanovic, J. (2021). Cognitive differences among first-year and senior engineering students when generating design solutions with and without additional dimensions of sustainability. *Design Science, 7*(1). doi:10.1017/dsj.2021.3
IDEO. (2022). Human-centered systems thinking: Syllabus. Retrieved from https://cdn.shopify.com/s/files/1/0259/7876/5396/files/Human_Centered_Systems_Thinking_Full_Syllabus_February_2022.pdf?v=1644615751.
Kannengiesser, U., & Gero, J.S. (2019). *Design thinking, fast and slow: A framework for Kahneman's dual-system theory in design.* Online: Cambridge University Press.
Kees, D. (2019). Design beyond design. *She Ji: The Journal of Design, Economics, and Innovation, 5(2)*, 117-127.
Keitsch, M. (2012). Sustainable design: A brief appraisal of its main concepts. *Sustainable Development, 20*(3), 180 -188.
Knapp, S., Gottleib, M.C., & Handlesman. M.M. (2017). Enhancing professionalism through self-reflection. *Professional Psychology: Research and Practice, 48(3),* 167-174.
Knauff, M., & Wolf, A.G. (2010). Complex cognition: the science of human reasoning, problem-solving, and decision-making. *Cognitive Processing, 11,* 99–102. https://doi.org/10.1007/s10339-010-0362-z
Mann, S. (2016). *Psychology: A complete introduction.* [Kindle version]. London: Teach Yourself: London.
McClelland, J.M. (2001). Cognitive neuroscience. In N.J. Smelzer & P.B. Baites (Eds.) *International Encyclopedia of The Social and Behavioral Sciences* (pp. 2133-2140). Elsevier, ScienceDirect.
Meadows, D.H., Randers, J., & Meadows, D.L. (1972). *The limits to growth: A report for the Club of Rome's project on the predicament of mankind.* New York: Universe Books.
Meadows, D.H., & Wright, D. (2008). *Thinking in systems: A primer.* Vermont, Canada: Chelsea Green Publishing.
Meyer, M.W., & Norman, D. (2020). Changing design education for the 21st Century. *She Ji: The Journal of Design, Economics, and Innovation, 6*, 13-49.
Miyake A., Shah P. (1999). *Models of working memory: Mechanisms of active maintenance and executive control.* Cambridge, UK: Cambridge University Press.
NASA. (2019, December 12). 2.0 Fundamentals of systems engineering. Retrieved from https://www.nasa.gov/seh/2-fundamentals.
Norman, D. (2009). The way I see it - Systems thinking: a product is more than the product. *Interactions 16(5),* 52-54.
Norman, D.A. (2016). When you come to a fork in the road, take it: The future of design. *She Ji: The Journal of Design, Economics, and Innovation, 2*, 343-348.
Pascal, B. (2018). Pensées (W.F. Trotter, Trans.). Digireads.com. (Original work published 1670).
Pourdehnad, J., Wexler, E.R., & Wilson, D.V. (2011). *Systems & design thinking: A conceptual framework for their integration* (Organizational Dynamics Working Papers, Working Paper #11-03). University of Pennsylvania, Scholarly Commons. Retrieved from http://repository.upenn.edu/od_working_papers/10.
Protzen, J-P., Harris, D.J. (2010). *The universe of design: Horst Rittel's theories of design and planning.* New York: Routledge.
Richmond, B. (1994). *System dynamics/systems thinking: Let's just get on with it.* Paper presented at the International Systems Dynamics Conference, Sterling, Scotland. Retrieved from https://iseesystems.com/resources/articles/download/lets-just-get-on-with-it.pdf.

Rittel, H. (1989). The state of the art in design theories and methods. Unpublished notes and manuscripts. In Protzen, J-P., & Harris, D.J. (Eds.) (2010). *The universe of design: Horst Rittel's theories of design and planning* (pp. 215-229). New York: Routledge.

Rhode Island School of Design: Centre for Complexity. Strategic Design Program. Retrieved from https://complexity.risd.edu/program/strategic-design-program/.

Rowe, P.G. (1987). *Design Thinking.* Cambridge, MA: The MIT Press.

Ryan, A. J. (2014). A framework for systemic design. *FORMakademisk 7*(4), 1–14. https://doi.org/10.7577/formakademisk.787.

Senge, P. (1990). *The Fifth Discipline: The art and practice of the learning organisation.* New York: Century.

Senge, P., Smith, B., Kruschwitz, N., Laur, J., & Schley, S. (2008). *The necessary revolution: How Individuals and Organisations Are Working Together to Create a Sustainable World.* London: Century.

Sevaldson, B. (2013). *Systems oriented design: the emergence and development of a designerly approach to address complexity*. Paper presented at the 2nd International Conference for Design Education Researchers, Oslo, 14-17 May 2013

Shi, Y., Queller, D.C.,Tian, Y., Zhang, S., Yan, Q., He, Z., Shu, L. (2021). The Ecology and Evolution of Amoeba-Bacterium Interaction. *Applied and Environmental Microbiology, 87*(2). 1-16.

Simon, H. A. (2019). *The Sciences of the artificial: Reissue of the third edition with a new introduction by John Laird*. Cambridge, MA: MIT press.

Snowden, D.J. & Boone, M.E. (2007) A leader's framework for decision making. *Harvard Business Review, 85(11).* 68-76, 149. PMID: 18159787.

Stanford University: Change labs. (2022). Retrieved from https://www.systemacupuncture.com/.

Strassmann, J., & Queller, D. (2018). *Kith and kin in amoeba-bacteria cooperation* (Washington University). National Science Foundation: Division Of Environmental Biology. Retrieved from https://www.nsf.gov/awardsearch/showAward?AWD_ID=1753743&HistoricalAwards=false.

Think Insights. (2022, May 12). *BANI: A new framework to make sense of a chaotic world?* Retrieved from https://thinkinsights.net/leadership/bani/.

University College London. (2022). *System thinking one-day workshop.* Retrieved from https://www.ucl.ac.uk/short-courses/search-courses/systems-thinking.

Vieira, S., Gero, J.S., Delmoral, J., Parente, M., Fernandes, A.A., Gattol, V., & Fernandes, C. (2019). Insights from an EEG study of mechanical engineers problem solving and designing. In Eriksson, Y., & Paetzold, K. (Eds.)*. Proceedings of the Human Behaviour in Design Conference, Bundeswehr University Munich (pp.23-34).*

Visser, W. (2009). Design: one, but in different forms. *Design Studies, 30*, 187-223.

Voûte, E., Stappers, P.J., Giaccardi, E., Mooij, S., van Boeijen, A. (2020). Innovating a large design education program at a university of technology. *She Ji: The Journal of Design, Economics, and Innovation 6*(1), 50-66.

Williams, H., & Lewis, J. (2020). Impressions on the current state of cognitive neuroscience in occupational measurement. In B. L. Parkin (Ed.) *Real-world applications in cognitive neuroscience* (pp. 123 - 138). Elsevier, ScienceDirect.

World Economic Forum. (2021, May). *Infrastructure 4.0: Achieving Better Outcomes with Technology and Systems Thinking* [White Paper]. Retrieved from: https://www3.weforum.org/docs/WEF_Infrastructure_Technology_Adoption_2021.pdf.

Woudhuysen, J. (2011). The craze for design thinking: Roots, a critique, and toward an alternative. Design principles and practice: *An international journal, 5*(6), 235-248.