WHAT I DON'T SEE, DOESN'T EXIST SCIENTIFIC ILLUSTRATION AS A SYNERGY BETWEEN SCIENCE AND ART

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Keywords

visual models in science, scientific illustration for the blind and partially sighted, science as art, subjectivity in science, cognitive aspects of scientific illustration

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Abstract

In recent years, advances in cognitive science have been rapidly expanding our comprehension of artistic creation, yet, since the beginning, the development of science itself has been guided by art, especially scientific illustration. This is particularly pronounced in biology and chemistry, where concepts cannot be imagined without visual models such as the structure of atoms and molecules. Similarly, much of biology is based on the principle that structure (dependent on form) determines function. The field's reliance on the visual conception of scientific models not only profoundly impacts our professional comprehension of fundamental scientific concepts but also poses a major challenge in communicating knowledge to the blind and partially sighted, especially those with congenital impairment, who have more difficulties in forming normatively accepted mental representations of abstract concepts. As they do not form a visual image, their visual representation can only correspond to a model or scheme, which guides understanding but may also be misleading due to the nature of visual perception. In this sense, we are all 'blind' to certain aspects of reality, though this manifests in various ways. Developing visualizations for the blind and partially sighted is essential, as these individuals can illuminate new aspects of scientific concepts that may be overlooked by the sighted.

THE IMPORTANCE OF A SCIENTIFIC APPROACH IN ART RESEARCH

Although visual representation in science may seem to play only a supporting role by illustrating otherwise highly objective findings, this is far from being the case. Visual art, in particular scientific illustration, serves not only to depict but also significantly guides our understanding of specific scientific concepts and directions. Despite having been separate worlds in the past, which still holds largely true today, art and science converge at least in their theoretical or philosophical cores, which is perhaps most evident in the field of experimental aesthetics, founded by the 19th-century German philosopher, physicist and experimental psychologist Gustav Theodor Fechner (1801–1887). He conducted experimental and scientific studies on individuals' experiences and behaviours resulting from exposure to works of art. In doing so, he shifted an originally philosophical field into the realm of empirically measurable natural sciences, both conceptually and methodologically (Berlyne 1974).

In the 20th century, experimental aesthetics evolved primarily towards cognitive psychology and neuroscience. The modern offshoots of this interdisciplinary field, psycho- and neuroaesthetics, investigate the perception, creation and individual responses to art through neurobiological experiments. Furthermore, they examine the interactions of humans (and other animals) with objects and scenes that trigger intense and diverse emotions related to aesthetic judgement and creativity. It is a distinctly transdisciplinary field, which is gaining increasing significance across various other disciplines, including education and medicine (Skov et al 2018; Chatterjee and Vartanian 2014). The founder of neuroaesthetics is the British neurobiologist Semir Zeki, who sees art as an example of the diversity among individuals' brains. The origins of this diversity can be identified, among others, through neurological approaches which can also aid in uncovering the mechanisms behind our ability to create and experience art (Zeki 1999, 2001 and 2002). Professor Zeki even argues that artistic creation actually serves as alternative means of exploring the brain. In one of his statements, Zeki asserts:

> The artist is in a sense, a neuroscientist, exploring the potentials and capacities of the brain, though with different tools. How such creations can arouse aesthetic experiences can only be fully understood in neural terms. Such an understanding is now well within our reach. (Miller and Miller, in: Shimamura and Palmer 2012, 357)

THE IMPORTANCE OF SUBJECTIVITY AND AESTHETIC PRINCIPLES IN SCIENCE

The presented view completely merges the originally highly theoretical philosophical field of aesthetics with the experimental scientific field of (neuro)biology. From this perspective, neuroaesthetics directly integrates two seemingly separate philosophical disciplines, aesthetics and the philosophy of science, which, from a theoretical standpoint, primarily intersect on the question of the extent to which reality is (or can be) objective or subject due to an individual's conception (Nagel 1974). In defining this problem from the stance of theory of science and philosophy, a key contribution was made by Zeki's contemporaries Thomas Samuel Kuhn (1922–1996) and Karl Raimund Popper (1902–1994). Kuhn defined the development of science as a sequence of small revolutionary changes that gradually destroy the existing paradigms and establish new ones. According to Kuhn, psychological and social factors are significantly more important for scientific revolutions than empirical scientific evidence, knowledge and arguments (Kuhn 2012). Consequently, scientific development and its history are strongly dependent on subjective factors. Popper, however, completely altered the direction of science development with his theory of critical rationalism, which opposes the previously established principle of demonstrability. He based the scientific method on the principle of refutability, which posits that within experimental sciences, particularly the empirical sciences, a theory cannot be confirmed but only refuted. From this point of view, only refutable scientific theories and findings are relevant (Popper 2012 and 2014). Thus, Popper definitively confirmed the dynamic nature of science and the importance of alternative interpretations.

Subsequently, building on the theory of critical rationalism, the Austrian philosopher Paul Karl Feyerabend (1924–1994) became the first who, within his own theory, directly placed science in the context of art by positioning the philosophy of science in the realm of aesthetics. While neuroaesthetics introduces the scientific method into the study of art, Feyerabend's model, conversely, highlights the importance of aesthetic principles in science (Feyerabend 2008, 93–95).

The background of intersections and unification of art and science have been contemplated by various Slovenian intellectuals, both in the past and in recent times. The status of the interconnection between science and art has been efficiently described by the Slovenian physicist and educator Gorazd Planinšič:

> The common view of science and art is that science is rational, objective and impersonal, while art is subjective and linked to emotions; moreover, scientific theories are believed to emerge directly from observations of the physical real world, while art is considered an expression of the human mind and emotions. Such a perspective is obviously wrong. […] Art and science are two ways of viewing the world. Both require a continuous comparison and verification of the real world around us against our mental images, representations and ideas formed in our minds. What is crucial to art and science is the ability to perceive, observe and, most importantly, interpret and generate new mental images. Experimentation is key to both fields, although it performs different roles. In natural science, experimentation serves to continually anchor theory to reality, whereas in art it promotes the development of new modes of expression.
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> (Planinšič 2008, 150, as cited in Campbell 2004 and Trstenjak, 1981)

In terms of the presented theory, both science and art engage in experimental exploration of the world, though their conceptual starting points and thus methodological approaches differ. In (natural) science, which includes biology, experimental approaches can be roughly divided into two groups. Scientific research typically involves *experiments that are controlled as precisely as possible* and conducted primarily in an adapted environment, i.e. a laboratory. In the context of art, this can be viewed as a type of scientific atelier or studio. The alternative is creating art outdoors or *en plein air*, where artists and their creative work are exposed to unpredictable natural conditions. In science, this corresponds to a *natural experiment*, which usually involves observing and describing the state of the (natural) environment. Describing phenomena on this basis has flourished several times in the past, most recently in the 20th century under the influence of the philosophy of logical empiricism, which argues that the logical integration of information acquired through the senses provides a correct picture of reality (Bogen 2009). The dilemmas and historical dynamics of logical empiricism in science and art were also explored by Feyerabend in his work *Science as Art* (*Wissenschaft als Kunst* 1984). He concentrated on the limitations and superficiality deriving from the idea of reflecting as accurately as possible the state of things (the theory of mimesis) or reproducing the mere physical manifestation of ideas. In the domain of art, this approach had already been criticized in Book 10 of Plato's *The Republic* (Feyerabend 2008, 95). The original idea of accurately representing reality through the medium of thought, without any addition by the author, is characteristic of both art and science. While art has succeeded in distancing from this idea, it continues to be highly present in certain facets of science, although substantial shifts can be observed. Creativity is also gaining prominence in scientific work, and significant scientific discoveries are increasingly credited not only to strict adherence to scientific procedures but, more importantly, to bold flashes of brilliance from scientists, as Feyerabend notes:

> [...] [G]reat science is not very different from great art. Clearly, expertise is needed in both cases. However, creative ideas are also demanded; in other words, neither scientists nor artists have to suppress their personality but can leverage it to their advantage in their research
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> (Feyerabend 2008, 101–103).

The result of scientific work are theories that aid in explaining the scientific view of reality, which, according to Popper's theory of scientific revolutions, can lead to progress only if it evolves over time, rather than simply expanding or accumulating. This is eloquently summed up by the thought: "The stone age did not end because the word ran out of stones" (*The Economist* 1999, 59). If new theories were not presented to both the professional and general public by their authors and proponents, science would serve only itself as a sort of 'scientific larpurlartism'. The importance of presenting scientific findings, which inevitably involves an element of subjectivity, is also emphasized by Miran Možina and Urban Kordeš in one of their writings:

> Reality and cognition are linked in a circular manner, always leading us to specific individuals or groups within a specific space and time, to a special world. (Možina and Kordeš 1998, 228–229) We defend our beliefs through a social process of conversation, attempting to persuade others to believe as we do. To understand the nature of human cognition is to recognize cognition as means of justification and defending of our beliefs, rather than to provide an increasingly accurate representation of Reality.
>
> (Možina and Kordeš 1998, 238)

THE BLESSING AND THE CURSE OF MODELS IN SCIENCE

Findings and conclusions are thus interpreted using models (Frigg and Hartmann 2006; Van Fraassen 2010) or as the versatile Slovenian researcher and university professor Milica Kač wrote:

> […] We conveniently forget it is only a model and often not a 'Ding an sich' (a thing in itself). This oversight sooner or later boomerangs back on us […]. Natural science entails the observation and study of nature, which cares little whether we have a suitable model. The first duty of a scientist is therefore to recognize the model. Their second duty is to become acquainted with the model and to accept its limitations very seriously and with all responsibility […]
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> (Kač, in: Raspor (ed.) 2013, 353).

Hence, we must be aware that despite our efforts to learn about objective reality, we still depend on subjective representations that are limited by our individual past experiences and cognitive schemata. Consequently, this means that any model, no matter how narrowly defined, will always be vague to some extent. A fuzzy concept defines an idea whose meaning can vary significantly depending on the context or conditions of use. Such a concept is objectively semantically fuzzy, but can give a sense of exactness due to its definable meaning, which can be better specified by providing a further explanation and establishing the context of use (Behlohlavek and Klir 2011). The study of the characteristics of fuzzy concepts and language pertains to the field of 'fuzzy semantics' (Zadeh 1971).

To better illustrate this, let us consider the example of a tree, which the Dictionary of Standard Slovenian (*Slovar slovenskega knjižnega jezika*) defines as 'a woody plant with a trunk and branches'. In practice, this description encompasses a number of similar yet diverse entities; for instance, trees include spruce and beech, which differ significantly in a number of characteristics. If we focus on the spruce, the Dictionary narrows its description to 'a coniferous tree with dark green pointed needles, pendulous cones and reddish-brown fissured bark'. Even though this narrows the meaning, a significant amount of ambiguity remains, which merely shifts from general characteristics, such as leaves or needles, to more specific ones, such as the shape or type of needles.

Thus, if several people talk about a tree or even a specific spruce, each subject of the conversation will create and operate with their own unique mental image of the object, regardless of how narrowly the image is formally defined (de Saussure 2018). The image an individual forms of a particular concept is primarily influenced by spatio-temporal and socio-cultural factors and therefore depends on their cognitive background. This means that the only way to approach objectivity—and make a fuzzy concept 'crisper' (i.e. clearly defined)—is through a combination of precise definition, understanding and consideration of the cognitive background of stakeholders (Reiss and Sprenger 2020).

In the case of more tangible concepts, such as trees, the phenomenon of vagueness is less pronounced. However, science often deals with highly abstract concepts, whose models can only be based on analogies with more tangible concepts. This, in turn, introduces additional vagueness or variability into the already cognitively conditioned understanding of individual concepts when reconciling abstract concepts between different stakeholders (Reiss and Sprenger 2020).

THE IMPORTANCE OF SCIENTIFIC ILLUSTRATION AND VISUAL MODELS IN UNDERSTANDING SCIENTIFIC CONCEPTS

Of all the senses, humans rely most on vision. It also dominates the field of scientific research, where the adage 'seeing is believing' is often invoked. As a result, science, at least traditionally, has been most closely linked to visual art, which encompasses a group of artistic genres that similarly rely primarily on vision (Jenks 2002). There are a number of other artistic genres that are perceived through the remaining senses. For instance, music is linked to hearing, while the literary arts are mainly associated with cognitive processes involved in abstract thinking (Bacci and Melcher 2011). Recently, the combination of different artistic genres and the development of new techniques, materials and expressive possibilities has given rise to numerous alternative forms of creativity. These have generated their own domains of contemporary visual arts, with photography as perhaps the most prominent example, alongside installation art, video and other new media (Brakeley and Sam 1979), which are gradually but steadily entering the realm of scientific illustration, as they broaden the range of expressive possibilities and interpretation. In this way they engage an individual's multi-sensory potential to familiarize a broader audience with concepts in a more holistic and inclusive manner. The importance of visualization, interpretation and dissemination of scientific knowledge has also been recognized and emphasized by Gorazd Planinšič in his discussion:

> Science needs art to communicate its achievements to the professional and lay public. Today, the presentation of scientific achievements […] is increasingly reliant on visual communication (through images, caricatures, films, computer simulations and animations), which can be more effective if the basic principles of design are understood and observed.
> (Planinšič 2008, 151)

This statement by Gorazd Planinšič holds significant relevance within the observed context. Indeed, the presentation of scientific achievements has always relied heavily on visual communication, which shapes our (subconscious) understanding of the concept introduced by the author through imagery and, even more significantly, influences how it is positioned within the broader context of the scientific canon (Heil 1983). Since the relationship between science and art is one of mutual support or 'symbiosis', it is clear that art also needs science for its development (Planinšič 2008, 151). The erroneous drawing of conclusions, which often sidetracks us in this context, primarily results from a superficial, one-sided understanding of this interdependence; according to this misconception, art merely enhances the added value of science, while being entirely reliant on science for the material resources and tools needed for the materialization of ideas. The shortcoming of this view lies in its neglect of science's dependence on art at the level of ideas, which subsequently lead to the development of technology, from which art, in turn, can benefit. The question is therefore similar to the dilemma of 'what allows what to exist – does the chicken precede the egg or vice versa'.

Depending on the nature of the models underlying individual fields of natural science, these fields can be divided into two broad groups. The first comprises fields such as mathematics and physics, which rely mainly on abstract models that do not necessarily require visualization to be understood. The second group, on the other hand, includes domains such as chemistry and biology, which rely almost exclusively on visual models. The entire contextual framework of chemistry and biology is founded on the structure of the atom and, consequently, that of molecules, as well as on the structure of biological elements at various organizational levels (ranging from molecular and cellular to tissue, organic, organismic and, last but not least, ecological levels) (Kozma and Russell 2005).

The structure and geometry of these elements determine both their aesthetics (i.e. their form) and their function, which is why basic patterns of form can be recognized in biology. These patterns occur in different contexts, and their combination creates the diversity of living beings (Siber and Ziherl 2017). One of the oldest and most prevalent geometric patterns in nature is the Fibonacci sequence, discovered by the Italian mathematician Leonardo Fibonacci (c. 1170–1240) as early as in 1202. The Fibonacci sequence is a sequence in which each succeeding term is the sum of the two preceding terms ($F_0 = 0$, $F_1 = 1$; $F_n = F_{n-1} + F_{n-2}$ for $n > 1$). Its pattern can be used to explain most biological spiral structures (Al-Suwaiyel et al. 2006). By studying soap bubbles and foam, the Belgian physicist Joseph Plateau (1801–1883) solved the mathematical problem of boundary conditions by attempting to identify the smallest surface area of a surface stretched over a given contour in space (Neimark and Vignes-Adler 1995). This finding is crucial, in particular, for understanding the shape of sessile aquatic organisms. The German psychologist Adolf Zeising (1810–1876) discovered that the individual elements composing the bodies of living organ-

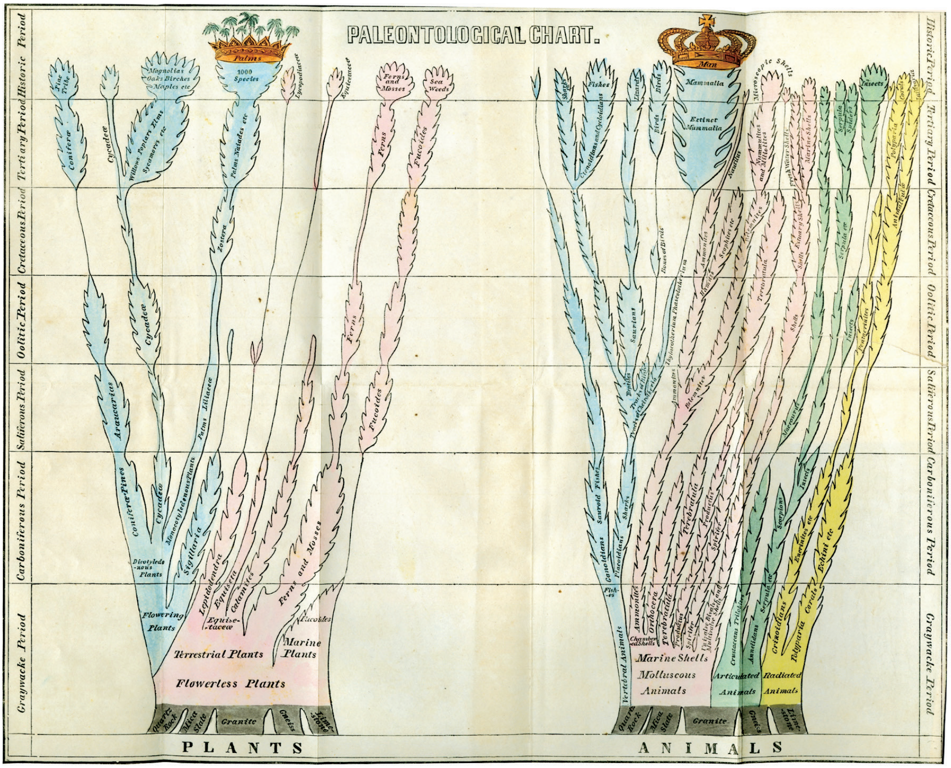

Figure 1: Edward Hitchcock: graphic representation of the system of life, i.e. a fold-out *paleontological chart* with humans at its top as the crown of creation, published in *Elementary Geology* in 1840 (Source: Wikipedia, CC).

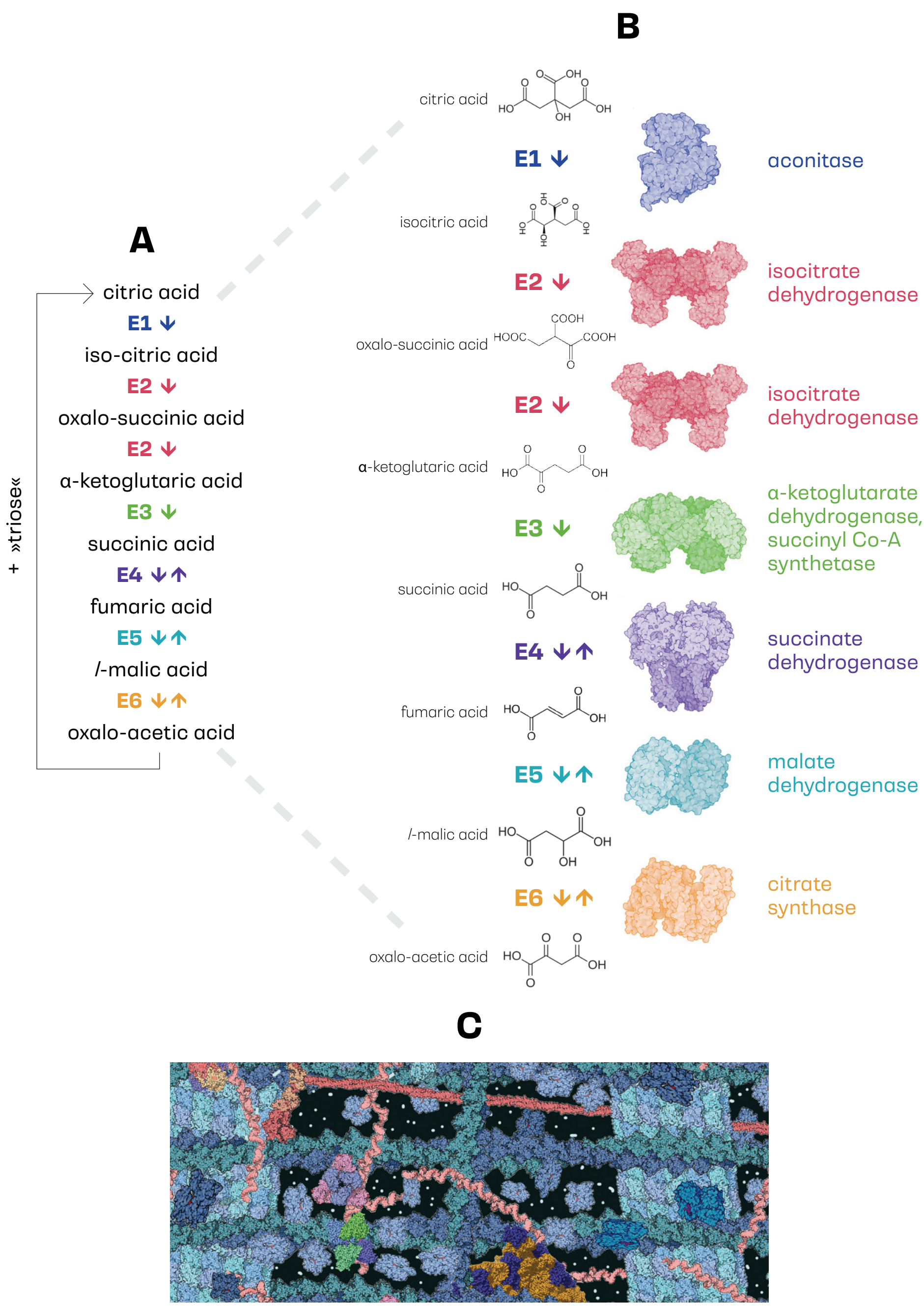

Figure 2: Model representing the cycle of citric acid.

A The first diagram of the citric acid cycle, published in 1937, based on the article by Hans Adolf Krebs and William Arthur Johnson (Krebs and Johnson 1937).

B A more representative model showing the structures of the individual enzymes, hidden behind the arrows, and the organic acids.

C A model attempting to present a more realistic image of the inside of a cell, crowded with different particles, which are not (necessarily) mechanically connected to each other.

isms are arranged according to the golden section (Zeising 1855). In 1952, the British mathematician Alan Turing (1912–1954) published a book titled *The Chemical Basis of Morphogenesis*, in which he presented an analysis of the mechanisms necessary for pattern formation in living organisms during the process of morphogenesis. He hypothesized the oscillatory nature of chemical processes, more specifically the Belousov-Zhabotinsky reaction. Reactions that present oscillations between inhibition and activation lead to the formation of various dotted, striped and spiral patterns in living organisms. Thus, the mathematician explained the growth pattern of most plant rosettes and the patterns observed on the surface of animal skin (zebra stripes, Dalmatian spots, etc.) (Turing 1990). Later, in 1968, the Hungarian theoretical biologist Aristid Lindenmayer (1925–1989) developed the L-system, which explains the fractal growth patterns in plants. The L-system is an alphabet of symbols that can be combined according to production rules to expand the string of symbols, transforming them into geometric patterns (Iannaccone and Khokha 1996).

On the basis of these examples, it can be deduced that chemical and biological processes are often translated into structure-independent (linguistic) forms by abstract mathematical and physical models. However, the understanding of these processes relies primarily on the presentation and comprehension of the underlying structural, visual models. The geometry of biological forms thus represents one of the closest points of convergence between biological science and art. In the following, we will examine two more abstract examples that further illustrate how neglecting the importance of visual representation can influence our perception of reality.

AN EXAMPLE OF THE PROBLEM OF VISUALIZING THE CLASSIFICATION OF ORGANISMS INTO A SYSTEM, I.E. THE TREE OF LIFE

Since the dawn of time, humanity has had a tendency to systematize. In the field of biology, this led to the emergence of a sub-discipline known as systematics, which focuses on the classification of living organisms into a system. Many natural scientists continue to organize organisms within the model called the 'tree of life'. In the tree of life, organisms are arranged forming a vertical composition, according to the analogy of a tree's growth. In different interpretations of the tree of life, humans are, in general, consistently placed on the highest branch. This approach was also applied by the American geologist Edward Hitchcock (1793–1864) in his 1840 work *Elementary Geology*, which is considered one of the first demonstrations of the idea that different recent organisms are related. Hitchcock further biblically emphasized the human's position with a crown (Figure 1), which is in line with a passage from Genesis (Gen. 1:27–28).

Such value-based hierarchical representations of the systemization of life on Earth, combined with other circumstances, subsequently led to biological anthropocentrism, the consequences of which are still evident today (Hitchcock 1856). In Western cultures, vertically ordered systems are linked to hierarchy, while horizontal axis is associated with equality. Therefore, the distinctly upright composition implicitly conveys the idea that the species represented higher in the tree are more evolved, more important or superior to those lower in the 'canopy'.

AN EXAMPLE OF A PROBLEM OF VISUALIZING BIOCHEMICAL PROCESSES

A more contemporary example of the disregard for the importance of visual interpretation can be found in biochemistry and molecular biology. In both scientific disciplines, visualization is often facilitated by diagrams of reactions occurring in living systems. These reactions, catalysed by enzymes, are typically represented as a chain or sequence, which can form a metabolic pathway, cycle or spiral (Nelson and Cox 2009). In these representations, it appears as if reactions (or enzymes themselves) link individual molecules into a complete chain. A well-known example of such metabolic processes is the citric acid cycle (Figure 2). The way to its discovery led to two Nobel Prizes for achievements in physiology or medicine. The first was awarded to Albert Szent-Györgyi (1893–1986) in 1937 for his research on fumaric acid and the second to Hans Adolf Krebs (1900–1981), who in 1937, assisted by his PhD student William Arthur Johnson, reconstructed the cycle (Krebs 1970). These representations suggest that metabolic pathways are similar to railway connections, leaving very limited freedom to the system. In reality, it is a free system where individual molecules move within the solution, and reactions, if concatenated, are linked thermodynamically rather than mechanically, as shown by the aforementioned representations. In this respect, a more fitting analogy would be that of air traffic, where the projected routes, unlike railway connections, are not absolute and allow for the free movement of bodies through space.

SCIENTIFIC ILLUSTRATION IN THE CONTEXT OF VISUAL DEFICITS

The two examples above clearly demonstrate how our understanding of scientific reality is based on its visualization and underscore the important and responsible role of scientific illustration, particularly in interpreting complex chemical and biological models. Thus, illustration is not merely a tool for communicating and popularizing science, as might be erroneously inferred from one of Gorazd Planinšič's statements (Planinšič 2008, 151) but rather an inseparable part of science itself.

Due to the interconnected processing of information received by brain from the different senses, some people may develop synaesthesia or unusual connections between certain areas of the cerebral cortex. This leads to an atypical perception, where a characteristic of a stimulus is assigned an additional characteristic, often from a different sensory modality (e.g. a colour is assigned to a particular sound), which does not replace the other. It is an automatic, involuntary and unidirectional phenomenon that can assume many forms. The additional characteristic can also arise within the same modality; for instance, a synesthete may attribute an additional visual characteristic, such as colour, to the visual stimulus of the letter ‘A’ (Ward 2013). The stimulus does not need to be entirely physically present—a synesthete can taste a word even in a situation where they can perceive it ‘on the tip of their tongue’ (Simner and Ward 2006). Synaesthesia involves an inducer, which triggers a perceptual event, and an associated concurrent, which refers to the additional sensory characteristics. For example, in a person who perceives blue when hearing the tone C, the tone C is the trigger and the colour blue is the concurrent (Grossenbacher and Lovelace 2001). For most synesthetes, this phenomenon is unidirectional; for instance, a particular tone is associated with a particular colour, but the colour is not heard when it is seen (Mills 1999). The concurrent is usually consistent and stable, whereas the inducer can be more flexible. For example, the visual perception of the letter ‘B’ might always trigger the perception of a specific shade of red, regardless of the font in which it is written (Grossenbacher and Lovelace 2001).

Many inducers are symbols (Glicksohn et al. 1992), which also appear in scientific illustration. Scientific illustration aims to harness the ‘synaesthetic potential’ present in everyone. This gives it a key advantage over photography, which merely captures the physical image as perceived by the camera or our eyes, including all details, whether more or less important. The brain then looks for certain patterns in these details, and the process itself differs slightly from person to person. Understanding the key cognitive processes of image formation in our brains allows for illustrations that guide and emphasize the desired patterns, muting the irrelevant ones, thereby facilitating a more unambiguous comprehension of the model itself. This implies that the (scientific) illustrator’s task is to create using primarily the material processed by our brains, rather than simply recreating the image perceived by our eyes.

This poses the question of how to present chemistry and biology, which are based on visual models, to individuals who are blind or partially sighted. When it comes to abstract concepts, even the sighted are, in a way, ‘blind’ and rely on creating visual models, which, in principle, assist in better understanding these invisible and intangible ideas. However, for the blind and partially sighted even very concrete elements, such as the shape and structure of individual organisms, present a challenge. The extent of the barrier between a blind or partially sighted individual and the classical visual models in science varies depending on the nature of the cause (aetiology) and reasons for the absence or lack of vision, which differ despite resulting in a similar consequence, that is, a more or less severe visual impairment. Impairment can derive from a defect in the sensory organ (the eye), the nerve that transmits visual information to the relevant brain centres or the visual cortex, which is the key centre for processing visual information. The perceived image is, in fact, the product of a number of brain processes that shape its final form and, ultimately, influence its impact on other cognitive processes, such as emotional reactions and memory.

In relation to this, recent findings have explained the long-known phenomenon of a reflex reaction upon perceiving certain shapes (e.g. elongated and uneven) that are associated with innate fears (e.g. of snakes), even in individuals with visual cortex damage, who lack the ability to form a visual image of perceived objects. These individuals, although unable to see the shape, respond to it due to the existence of an afferent pathway from the pulvinar to the amygdala. This pathway enables a defensive fear response to certain evolutionarily relevant forms that pose an imminent threat (McFadyen et al. 2019).

Besides the various aetiologies leading to partial sightedness or even blindness, these conditions also have diverse underlying causes. They can occur as a loss or deterioration of a person's vision, potentially giving rise to the development of synaesthesia, in which the lost modality (i.e. vision) becomes a concurrent. Although the primary source of information is no longer present, the visual cortex, if preserved, can develop a multimodal connection with other parts of the brain over time (ranging from days to years) (Ward 2013). In practice, a person may, for example, see a specific visual image simultaneously with a particular touch, sound or other stimulus.

The second group consists of individuals with congenital partial sightedness or blindness who have never had the chance to form a visual representation comparable to that of sighted people. While this group comprises a relatively small portion of the population, their cases are the most challenging in the examined context. As their world and the visual world of the sighted never intersect, it is nearly impossible to create a pictorial translation between the two. If a field is almost entirely reliant on visual models, it is virtually inaccessible to people with congenital blindness. Consequently, they are deprived of a large part of the scientific canon, which remains unavailable to them due to the absence of a mechanism for its perception, processing and further contextualization.

EXCEPTIONS WHICH INDEED PROVE THE RULE

At a global level, there are a few (congenitally) blind or partially sighted individuals who have built successful scientific careers, including in chemistry and biology, such as Dr Cary Supalo, Dr Henry Wedler, Dr Stephanie DeLuca and Dr Geerat J. Vermeij (Minkara 2024). Nevertheless, their proportion is still negligible compared to the total population of blind and partially sighted people. A key reason for this is the insufficient accessibility of fundamental models pertaining to the observed scientific fields, which becomes evident as early as in primary education. Blind and partially sighted students in Slovenia, who are usually enrolled in adapted educational programmes, primarily learn chemistry and biology through descriptive methods. Although some structure-oriented models can be partially translated into 3D images or text accessible in braille, a complete adaptation is nearly impossible, particularly within the normative context of sighted individuals, which prevails in the scientific community (*Independent science* 2024).

Many blind and partially sighted students do not pursue their education in a mainstream grammar school programme culminating in the general baccalaureate, which is the most common educational route among their sighted peers. An even smaller number of blind and partially sighted students opt for chemistry or biology as a baccalaureate subject. Consequently, in Slovenia, this issue is seldom tackled on a conceptual and professional level. The severity of the challenges faced by the blind and partially in comprehending chemical and biological concepts has been recently underscored by the case of a student with progressive vision loss. Alongside her sighted peers, she attended the mainstream grammar school in Ljutomer, choosing chemistry as the elective baccalaureate subject to complete the educational programme (Tomažin 2023). Despite the general baccalaureate subject catalogue providing for special needs adaptations (Alif et al. 2021), a significant barrier was encountered in this instance concerning a foundational chemistry concept: molecular structure. According to the student's chemistry teacher, she had previously struggled to follow lessons in science subjects such as chemistry and biology, mainly due to the lack of appropriately adapted learning materials (Tomažin 2023).

Despite an extensive search, the educators and the two students who prepared the final project found no suitable system which would enable the blind and visually impaired to engage in structural chemistry learning and co-creation, compelling them to address this challenge themselves. Building upon the SMILES computer program, they developed a linear notation for chemical compounds, using the already established linear mathematical notation system as a reference. Unlike chemistry, mathematics is based to a greater extent on abstract models, which makes it more accessible to the blind and partially sighted. The proposed linear notation for chemical compounds was annotated with the feedback from a sample group of blind and partially sighted people and suitably adjusted according to their comments (Tomažin 2023).

The obtained linear structural notation of chemical formulae can be used to represent most compounds, though not all of them as foreseen by the IUPAC nomenclature. Additionally, some otherwise feasible notations of compounds present readability challenges and are more difficult for blind and partially sighted people to recognize. The project's main objective was primarily practical:

to enable blind and partially sighted students to undertake their final examinations and to follow chemistry and biology lessons on a daily basis (Tomažin 2023). Despite the notable success of the case in question, it is essential to acknowledge that the student's vision loss was gradual, allowing her to acquire at least fundamental visual experience prior to vision loss, which contributed to her ability to tackle structural chemistry with some more ease. The challenge, particularly difficult by itself, is even harder for people who have been blind since birth.

INSTEAD OF A CONCLUSION: THE POTENTIAL FOR CONTRIBUTIONS BY THE BLIND AND PARTIALLY SIGHTED IN SHAPING VISUAL MODELS

In biology, similarly to chemistry, despite the advancements in molecular techniques, the classification of organisms and the study of their properties primarily rely on their structure and appearance. The differences between individual organisms are often very subtle and part of a broader context that, in the conventional format, is largely, if not entirely, inaccessible to the blind and partially sighted. This issue has also been addressed by the exceptional Brazilian photographer Sebastião Salgado, whose emotionally charged photographic expression transcends mere documentation of reality. Salgado's primary focus lies in environmental and anthropological photography, which he has recently aimed to make more accessible to the blind and partially sighted by undertaking a project that has led to a special edition of a relief photography book. Despite the extreme difficulties in attempting to enable a comprehensive understanding of natural science concepts, which are already challenging for the sighted, there nevertheless exist approaches to overcome barriers for the blind and partially sighted (Salgado 2023), ultimately benefiting everyone.

From the outset, sighted people are influenced by a long-standing history of conceptualization, where the available models may present a single, occasionally rather problematic interpretation amidst a variety of potential ones. The majority of alternative interpretations do not come to the fore or even see the light of day due to the predominance of established models, hence it is crucial that we strive towards 'visualizing' chemical and biological concepts in a manner that is accessible to blind and partially sighted people. The blind and partially sighted can provide us with an alternative view of established natural science concepts or even develop new approaches that do not yet exist. Projects like the International Summer School in Kaverljag, Slovenia, with its transdisciplinary team and methodological approach, have proven effective in this regard on several occasions, not least in the development of the linear notation for chemical compounds' structural formulae, as presented above.

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