

FROM THE HISTORY OF PHYSICS

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X-men: humans with an unusual interaction between receptor systems who construct a world of new images within themselves
(on the 140th anniversary of the birth of Academician P P Lazarev)

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Abstract. **Academician Petr Lazarev's scientific and organizational activities are briefly described. He predicted, first, the law of interaction between various sets of receptors that occurs in solving problems by humans and, second, the existence of a special type of their special interaction in which two or more receptor channels are either synchronized or combined into a single channel. The second option is referred to as synesthesia. Half a century later, the interest in studies of this phenomenon became widespread.**

Keywords: Academician P P Lazarev, biophysics in the Soviet Union, synesthesia

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From the conclusion of academician A N Krylov, member of the commission of the Presidium of USSR Academy of Sciences, concerning the report by P P Lazarev "Influence of Singing on Vision": "...the report should have been entitled 'The influence of irritation of the brain's auditory center on the visual center' using, for certainty, the respective Latin anatomical terms; then, the title would not have caused misunderstanding...."

Academician *A N Krylov* [1]

1. Introduction

This article is devoted to the area of biophysics originating in one of the studies by Academician Pyotr Petrovich Lazarev. On April 14, 2018, the scientific community marked the 140th anniversary of his birth.[1] It is noteworthy that, 100 years ago (April 1918), Lazarev founded the journal *Uspekhi Fizichekikh Nauk* [6–8], which to this day remains one of the highest impact-factor Russian scientific journals. P P Lazarev succeeded by dint of talent and perseverance in establishing a journal that covered practically all branches of physics and related sciences to promote the rise of physical research in the country going through a difficult time.

[1] See articles [2–5] in *Uspekhi Fizichekikh Nauk* about the life and creative work of Pyotr Petrovich Lazarev.

Dictionaries and encyclopedias are written in a cold, matter-of-fact style. Witnesses of dramatic events take away bright memories of them as they depart from this life. Some participants in past events by chance become iconized and go down to posterity as subjects of veneration, while the names of others fall into oblivion. History must be treated with respect, without going to extremes.

In the article under the title "Birds and frogs in mathematics and physics" [9], the American theoretical physicist F Dyson divided scientists into two groups. Birds fly high in the air and survey broad vistas of mathematics and physics out to the far horizon. They delight in concepts that unify our thinking and bring together diverse problems from different parts of the landscape. Frogs live in the mud below and see only the flowers that grow nearby. They delight in details of particular objects and solve problems one at a time. Both 'birds' and 'frogs' contribute to the progress of science. P P Lazarev happened to be a bird.

In continuation of this idea, I would like to note that T P Kravets, corresponding member of the USSR Academy of Science (1876–1953), wrote in his paper "The creative career of academician P P Lazarev" [10]: *P P showed great interest in the psychology of creative work and frequently referred to the book* Grosse Manner *by W Ostwald* [11], *who categorized scientists into 'classical' and 'romantic'. The former tend to develop established lines to perfection working quietly all by themselves*; *they clearly see the future lines of research that they perform and complete them practically unassisted. The latter rather try to rely on intuition and are more likely to open new unexpected alleys for research*; *they know only the direction in which they wish to go out into the unknown and need disciples and co-workers to solve the arising problems. P N Lebedev, the outstanding physicist and our common teacher, was certainly a romantic, and Lazarev knowingly chose to travel the same road, even if unwillingly, against his character and habits....*

One more characteristic of Lazarev can be found in a letter from P N Lebedev, his teacher, to the well-known Russian biochemist L A Chugaev (1873–1922) dated October 17, 1910: *In my opinion, P P Lazarev is a highly gifted researcher with an inexhaustible fund of scientific ideas and a brilliant career in the future*; *he is an excellent teacher who heartily likes what he is doing, wishes and knows how to bring pupils together*; *more than that, he is a clever and good man. I can say with a safe conscience that Lazarev is much more endowed than other physicists, including myself, in terms of both the creative potential and the ability to establish a scientific school* [12–14].

The objective of the present publication is to show, first, that authorities often find it hard to come to terms with the existence of free-minded scientists and, second, that recognition sometimes comes not to those who propose an explanation for a new phenomenon but to those who understand and popularize the original idea of the discoverer.

2. Excerpts from the biography of Academician P P Lazarev

2.1 History of the Moscow scientific school of physics

To demonstrate the wide spectrum of Lazarev's scientific interests, suffice it to mention a variety of problems, from molecular physics to geophysics, considered in his papers that appeared in the very first issues of *Uspekhi Fizicheskikh Nauk*, the journal of which he was the founder [15–27]. All in all, P P Lazarev authored more than 500 scientific articles, books, and brochures.

Academician P P Lazarev (14.04.1878–24.04.1942)

In autumn 1977, the disgruntled Academician V V Shuleikin came to Academician A A Baev, then academician-secretary of the Department of Biochemistry, Biophysics, and Chemistry of Physiologically Active Compounds, USSR Academy of Sciences, to express disappointment that the department with the term 'biophysics' in its name appeared to disregard the coming 100th anniversary of the birth of P P Lazarev.

Why V V Shuleikin was so active in connection with the anniversary of P P Lazarev? V V Shuleikin was formerly a worker at the Institute of Physics and Biophysics, PCH RSFSR,[2] set up by Lazarev and based at the Physical Institute [28, 29] that later gave rise to the P N Lebedev Physical Institute of the USSR Academy of Sciences [30] and most of the Moscow institutions engaged in biophysical research.

V V Shuleikin headed the Black Sea Hydrophysical Station that he organized at Katsivelli, the South Coast of Crimea, in 1929 (with the support of P P Lazarev). Based at this facility, Shuleikin conducted a large series of sea physics and biophysics research. Specifically, he tried to elucidate why some fish and marine mammals (e.g., dolphins) can swim so quickly with low energy consumption, how flying fish 'fly', why movements of bird flocks and fish schoolings provide more advantages than those to individual animals, and how and why marine animals feel an approaching storm and go

[2] PCH RSFSR — People's Commissariat of Health of the Russian Soviet Federative Socialist Republic.

down deep long before it comes to avoid being crashed ashore by the waves. He managed to obtain answers to many of these questions. P P Lazarev had a high regard for the abilities of then yet young researcher and propagated his work, as seen from the comments [31] on Shuleikin's book *Physics of the Sea* [32]. Naturally, Shuleikin, being a grateful disciple, assumed a major burden to prepare for the jubilee celebrations.

Forty years ago, A A Baev asked me to prepare a lecture on the role of P P Lazarev in the development of biophysics in this country to be delivered on behalf of our department [33]. Reading Lazarev's, having talks with V V Shuelikin and especially professor Ya L Shekhtman (who worked with Lazarev for many years and later headed a laboratory at our institute in Pushchino), I came to understand many situations in Lazarev's life.

For the purpose of this narration, it is important to emphasize that Lazarev, when a student, attended the famous colloquiums run by P N Lebedev in the early 20th century at the Stoletov library of the Physical Faculty of Moscow University. Lebedev noticed the humble but capable young Pyotr Lazarev. Further events are well known and have been described many times. The archive of the Russian Academy of Sciences prepared an illustrated slide film about the life and creative work of Academician P P Lazarev on the occasion of the 135th anniversary of his birth. It is freely available to anyone.[3] I shall outline only a few episodes from the life of P P Lazarev either missed or incompletely presented on this website.

Police repressions at the beginning of 1911 provoked student protests at Moscow University. The rector and his deputies were sacked by the Minister of Public Education. One hundred twenty-four professors and lecturers, including the 45-year-old professor P N Lebedev and 33-year-old private assistant P P Lazarev, left the university in protest. Lebedev died following a long illness in March 1912. P P Lazarev headed his laboratory outside the Moscow university, where the Institute of Physics and Biophysics was set up in 1919. The laboratory was funded by voluntary donations from the Kh L Ledentsov Society[4] and other sponsors [28]. Such is the brief history of P P Lazarev's early administrative career [33, 34].

2.2 Scientific achievements

P P Lazarev was elected full member of the Academy of Sciences in 1917 it is significant that he was recommended by leading Russian scientists, such as physiologist I I Pavlov, mathematician and mechanical engineer A N Krylov, mathematician V V Steklov, mineralogist, geochemist, and environmentalist V I Vernadsky, and chemist N S Kurnakov. The mathematical basis of *the ion theory of excitation* [35] was considered to be the most important contribution of Lazarev. Today, this theory is only of historical interest. But at that time there was neither detailed knowledge of signal substances nor a clear understanding that minor events in nonlinear biosystems may have the most serious consequences, and that not only ligand[5] concentrations but also propagating targets with a high amplification factor of effect and response are of primary importance in receptor-mediated processes. By the way, Academician S I Vavilov, one of Lazarev's pupils and later elected president of the Academy of Sciences, demonstrated that under dark adaptation conditions, our eye is capable of single-photon perception [36] (as Lazarev had also mentioned in his earlier simple calculations) [20]).

The second contribution considered as Lazarev's achievement relates to photochemistry [37]. Attacks from Timiryazev, sometimes very sharp [38] as regards the importance of light source intensity (the number of photons) compared with that of radiation frequency in photochemistry was rather meaningless and appears to have been due to personal animosity between the two scientists. Physiologist Timiryazev was on friendly terms with P N Lebedev and hoped that the latter's co-workers would show interest in studies at the borderline between physics and plant physiology. However, Lazarev, who became the head of Lebedev's laboratory after his death, had different plans. He sought to elucidate the sun ray behavior in the living eye rather than in plant chlorophyll, i.e., "to observe disintegration of visual purple." Certainly, Lazarev had perfect insight into the essence of photochemistry. The fact is that as early as 1887 Heinrich Hertz observed that a spark discharge between two hollow zinc spheres was much more pronounced when one of them was illuminated with UV light [39]. One hundred years later, A G Stoletov formulated a law saying that the speed of photoelectrons knocked out by incident light grows with its frequency and the number of electrons knocked out by photons is proportional to light intensity [40]. In other words, Timiryazev's criticism was to no purpose. As is known, the definitive mathematical interpretation of the photoeffect was proposed by Albert Einstein in 1905 [41]. Lazarev not only was well aware of Einstein's work but also knew him personally, as confirmed by photographs found in his archive (see photo 1 and the group photograph from [42] showing participants in the Week of Russian Science held in Berlin in 1927).

The cartography of the Kursk magnetic anomaly under the supervision of P P Lazarev in 1918 used to be considered a breakthrough in geophysical science at the time of the establishment of Soviet power [26, 27]. In my opinion, it was

Photo 1. Left to right: P P Lazarev, Niels Bohr, and Albert Einstein (Berlin, Week of Russian Science, 1927).

[3] http://www.arran.ru/bookreader/publication.php?guid = 7FA5B941-BC38-4EA2-8F3D-38E935194259&ida = 1&kod = 9#page/1/mode/1up.

[4] Kh S Ledentsov, the first guild merchant and philanthropist (1842–1907), organized one of the first funds for science development and implementation. The Ledentsov Society became an independent nongovernmental organization that promoted scientific and technical progress. It existed for about a years (1909–1918).

[5] Ligand (from Latin *ligare* — to bind) — collective term for microparticles (atoms, ions, or molecules) binding to the receptor center (acceptor).

important but purely technical work forced to be done out of necessity when Russia was isolated from the rest of the world by the Great October Socialist Revolution (now sometimes referred to as the 'Bolshevik upheaval'). A similar survey had already been conducted before the revolution at the magnetically anomalous territories of the Kursk and Oryol provinces under the guidance of professor E E Leist. The scientific materials appeared in Germany where Leist died in 1918. A huge sum of 50 mln gold rubles was asked to get them back. Lazarev consented to undertake a repeat exploratory study at a lower cost in the shortest possible time. He was not the first, but this work gave him an opportunity to prove himself to be a man of no common executive abilities.

I am of the opinion that at least three biophysical investigations guided by Lazarev greatly contributed to the progress in science and still continue to be of great interest. Far from every researcher may boast major breakthroughs that laid the foundation of new mature scientific disciplines.

Lazarev and his disciples demonstrated in their dark adaptation experiments the different sensitivities of the eye depending on a person's age, on the one hand, and on astronomical time, on the other hand. It follows from Lazarev's published articles that he spent a few decades proving that the observed fluctuations were not an artifact. He discovered, by averaging rapid fluctuations, relatively slow oscillations and their periodicity with characteristic times (days, months, seasons). He appears to be the first to have revealed regular 24-hr periodicity (circadian rhythm) in the work of the human visual system [43]. This result merits special attention bearing in mind its relevance to problems related to aging and the biological clock (specifically, the influence of internal genetic and external factors on their accuracy).

The second continued study was devoted to mimicry, i.e., protective coloration in animals. In 1940, Lazarev briefly described it as follows: "In practical terms, mimicry is very important in warfare. The Institute of Physics and Biophysics not only proposed a well-developed color masking theory to be used in military science (1918–1923), but also demonstrated through various examples its high efficiency" [28]. What are the main results and outcomes of this theory?

P P Lazarev and V A Gamburtsev, his co-worker, obtained reflection spectra of green leaves and pigments responsible for the protective coloration of green-colored animals, e.g., frogs and insects. They showed that spectra of their skin pigments in the visible range are roughly identical to those of chlorophyll despite the different chemical compositions of plant and animal pigments. This explains why these creatures are sometimes invisible. Publication of these observations was followed by the next logical step. The spectrum of an object and its chemically different background can not be identical over the entire range of electromagnetic waves. Therefore, the object can be seen against the background if the reflection pattern of either of them is obtained at three wavelengths, provided the spectra do not overlap. The farther apart the wavelengths are spaced (within the UV to IR range), the more likely the object will be detected, even if its chemical composition is only slightly different from that of the background.

This effect was realized in 'zonal chambers' installed on artificial Earth satellites in the second half of the 20th century. Photographs of Earth's surface were taken from space simultaneously at three different wavelengths spaced far from each other over the visible spectral range. A spy satellite carrying such chambers recorded, in accordance with Lazarev's theory, all objects, regardless of their background. Presently, satellites equipped with zonal chambers play an important role in monitoring Earth's surface across the vast territory of our country for the purpose of environmental protection, the rational use of biological resources, forest fire control, etc. In other words, the ideas of Lazarev and his coworkers are being implemented 50 years after their publication.

In what follows, attention is focused mainly on Lazarev's third study concerning coupling and the mutual influence of human receptor systems (see Section 3).

2.3 First steps of biophysics in Soviet Russia

To begin with, let us see how the first Soviet Institute of Physics and Biophysics affiliated with the RSFSR People's Commissariat of Health was established in 1919. I heard its story from Prof. Y L Shekhtman (1892–1984), who at that time was a nonstaff worker in Lazarev's laboratory [29, p. 88]. The People's Commissar of Health was N A Semashko, with whom Lazarev was on friendly terms.

In August 1918, V I Lenin, 'the leader of the world proletariat', was wounded by Fanny Kaplan, member of the Social Revolutionary party. There were more potential killers wishing to get rid of the Bolshevik leading personality in the struggle for power and political influence. It still remains unclear whether it was actually weak-sighted Kaplan who wounded Lenin. The best representatives of the medical profession were recruited to treat Lenin and a special commission was convened comprising N A Semashko (chairman), V A Obukh, V M Bonch-Bruevich, B S Veisbrod, N Vinokurov, M I Baranov, V N Rozanov, and Prof. V M Mints. At the very first meeting of the commission, its members agreed that an X-ray study of the patient was urgently needed to determine the location of the bullets in the body and the type and extent of the injury.

V M Bonch-Bruevich wrote in his memoirs [45]: *September 7, 1918. 7 p.m. Lenin's general condition allows him to undergo an X-ray examination to be performed by Doctor Budinov this evening. It was decided to carry out chest radiography using a very heavy mobile Roentgen apparatus. I had to ask Red Army men to choose the four strongest among them to noiselessly transport the heavy appliances to the small cramped room where Lenin lived... .*

The X-ray image thus obtained was of poor quality but provided a general picture of tissue damage and the bullet location. This case gave an impetus to the development of high-quality X-ray instrumentation in this country. N A Semashko was charged with addressing the problem.

X-rays are known to have been discovered by W K Roentgen in 1895. Very soon, X-ray tubes found application in medicine. In Russia the first one was made within a year after the discovery. Routine examinations of patients began in February 1896 based at the Military Medical Academy. During the First World War, a mobile X-ray screening trailer mentioned in the above citation was constructed [46] with the participation of P P Lazarev. The high-voltage transformer was the most vulnerable component of the first X-ray machines. Anode voltage needed to be increased to 60–80 kV to generate X-rays, i.e.. the ratio of primary to secondary windings had to be at least 1/1000. Coil winding machines and high-quality wire for the purpose were lacking in the country. It was extremely difficult to manually apply windings of poor-quality wire, the main problem being insulation. High voltage caused transformer breakdowns and failure of the X-ray machines. In mid-1918, there were practically none of them left in the hungry country ruined by the war and political instability.

From the memoirs of V N Rozanov, member of the commission [45]: *On the evening of April 20, 1922, N A Semashko gave me a phone call and asked to see Vladimir Ilich the next day, because professor Borkhardt was expected to come from Berlin for consultation and finding ways to remove bullets from the patient's body. First, Vladimir Ilich had to undergo an X-ray examination with multi-directional scanning using the best available apparatus placed at the institute headed by Academician P P Lazarev* [6]*.... The study completed, Vladimir Il'ich wished to see the institute guided by P P Lazarev. The visit proved very short, because as soon as Vladimir Ilich entered the room where Lazarev stored materials concerning Kursk magnetic anomaly, he asked the host to tell him about this phenomenon. He listened very attentively and seemed to be deeply absorbed in the story. When leaving the institute, he asked Lazarev to keep him informed about developments in the area.*

The X-ray machine at the Institute of Physics and Biophysics was operated by technician Ya L Shekhtman already mentioned above. He could not hear the rest of the conversation between P P Lazarev and V I Lenin during the film drying procedure. Lazarev seemed to be satisfied with the result of the visit of the Bolshevik leader. The content of the talk can be deduced from the fact that both the academic standing of P P Lazarev and the attention to biophysics at the Academy of Sciences reached a climax at that period. The Institute of Physics and Biophysics gave rise to many biophysical research institutions, including our Pushchino institute. After Prof. Shekhtman retired, he was repeatedly invited to local schools to tell children how he met Lenin. Thus, the birth of biophysics in the USSR should be dated not to the historical shot of the cruiser Aurora (as the official press termed it) but to the shot of Fanny Kaplan.

2.4 Twists and turns of fate

On the occasion of the 200th anniversary of the Russian Academy of Sciences, it was proposed that P P Lazarev, an eminent member and a man of wide scientific interests, present a historical sketch on the development of exact sciences in Russia over 200 years at a ceremonial meeting to be held on September 13, 1925. He coped with this task brilliantly, providing the report with his own hand-drawn portraits of outstanding Russian scientists [47].

P P Lazarev was never a critic of the Soviet regime. On the contrary, he was on friendly terms not only with N A Semashko, the People's Commissar of Health, but also with Marshal M N Tukhachevskii, WPRA [7] chief of staff. Unfortunately, he seems to have overestimated the safety of his position and overstepped the bounds of free-thinking allowable in Soviet Russia. Talent and conscience sometimes prevail over instinct of self-preservation. Lazarev made several careless statements in his speeches and presentations. In January 1929, he argued against a second ballot of communists who had failed election to the Academy of Sciences membership as running counter to its Charter (it nevertheless did not preclude a second vote). As a result, he was put on notice by the OGPU.[8] A series of denunciations followed his lecture on Friedrich Engels's *Dialectics of Nature*.

In January 1931, the journal *Bolshevik*, the official press organ of the Central Committee of the Communist Party, published an article by the philosopher E Kol'man under the title "The saboteurs in science" [48], stating that some researchers were sabotaging the building of socialism in the Soviet Union. The list of saboteurs included P P Lazarev, who was arrested in the early morning hours of March 5, 1931.

It is curious to see how Lazarev viewed Engels's *Dialectics of Nature* in the explanatory note, 'My political creed' [49] probably requested the OGPU, Lazarev wrote: *After scrutinizing the original work by Engels and its further development, I came to the conclusion that this lifework of the author can be interesting only by virtue of his name. His doctrine has not brought in anything new, nor will it bring anything in the future. I tried to confirm this conviction of mine by a number of examples. My view is shared by many renowned scientists in western Europe, such as Einstein. It is therefore natural that my studies are permeated by the spirit of physical chemistry alone and there is no room in them for dialectic materialism. This statement refers not only to my scientific work but also to the education courses that I wrote. I believed that it is most important for a student to know facts, since he can come to the knowledge of their philosophical context in the course of time. Therefore, I, unlike other communist authors (e.g., Timiryazev), did not include arguments based of the postulates of dialectic materialism in my courses.*"

Lazarev was removed from the posts of director of the Institutes of Roentgenology and Biophysics by the order of the People's Commissariate of Health. The Institute of Biophysics headed by him was closed and its staff members were signed off. It became known later that Lazarev was about to be accused of espionage on the pretext of his trips abroad for lecturing and correspondence with many foreign scientists, However he was freed in September 1931. A large-scale crackdown on dissent and terror in the country have not yet reached their future scale. Lazarev survived, but he was exiled to the city of Sverdlovsk in the Urals. His wife committed suicide while he was in prison. Had he been arrested in 1937 or later, he would have been shot or shared the fate of N I Vavilov [34].

Lazarev was allowed to return to Moscow at the end of February 1932, but the arrest and exile ruined both his reputation and health. The attitude of the official press changed too. The rest of his life can be described by the oriental fable 'Even an ass can kick a prostrate lion'.

3. Search for methods and means of coupled sight and hearing study

3.1 "Influence of Singing on Vision"

It was not long before an opportunity 'to kick' offered itself. Lazarev presented the report "Influence of Singing on Vision" based on a series of his earlier studies [50] in which he developed the idea of reciprocal influence of the organs of hearing and vision [51]. The *Izvestiya* newspaper of

[6] N A Semashko fulfilled the assignment of the commission: Institutes of Roentgenology and Biophysics were set up in 1919. The X-ray machine at the Institute of Biophysics was operated by the then 30-year-old technician Ya L Shekhtman, who was afterward an active participant in the creation of the Soviet X-ray industry.

[7] WPRA — The Workers' and Peasants' Red Army.

[8] OGPU — Joint State Political Directorate set up on November 14, 1923 and affiliated with the Council of the USSR People's Commissars. At that period, the OGPU was headed by V R Menzhinskii, the successor of

27.12.1937 published a feuilleton against Lazarev entitled "Vision and singing or a torch with fly ashes" penned by the Tur brothers.

The academy set up a commission to audit and check up on the activity of Academician P P Lazarev at the expense of the state. The commission, comprising academicians S I Vavilov, A N Krylov, L A Orbeli, and A A Rikhter, was chaired by Academician A N Bakh. The members of the commission did their best to help Lazarev by referring to his eminence in science and pointing out only minor deficiencies and inaccuracies in his report. Suffice it to read the conclusion of the mathematician and mechanical engineer A N Krylov that appeared in public media only in 1956, i.e., 3 years after the death of Stalin [1]. In 1938, a fierce campaign of slander against P P Lazarev and his 'pseudoscientific theory' was launched in the press. All these attacks completely undermined Lazarev's health and he acquired a whole range of diseases, including epilepsy, diabetes, and finally stomach cancer. P P Lazarev was evacuated from Moscow during World War Two and died in 1942.

What follows is focused on an analysis of Lazarev's paper "On mutual influence of the organs of vision and hearing " [51] and the report "Influence of Singing on Vision" that gave occasion for the harassment and persecution of the scientist. Lazarev sought to elucidate mechanisms of brain work. The idea was half a century ahead of its time. This problem, of interest not only to biophysicists and neurophysiologists but also to physicists and engineers engaged in the development of coding and decoding 'artificial intelligence' systems, is not completely resolved, despite a wealth of new experimental data. This unusual phenomenon is discussed below in greater detail.

3.2 Lazarev's reasoning about the mutual influence of receptor systems

Numerous experiments by the German psychologist Ernst Weber demonstrated that the tactile receptor system controlling perception in humans has a logarithmic rather than linear sensation scale. In 1860, another German psychologist, Gustav Fechner, the founder of psychophysics and psychophysiology, formulated based on these observations the so-called psychophysical law [52] stating that the strength of sensation E is proportional to the logarithm of stimulus intensity U:

$$E = \alpha \log \frac{U}{U_0} \,, \tag{1}$$

where α is a constant depending on the intrinsic characteristics of a concrete person, U is the stimulus intensity, and U_0 is the lower borderline value of stimulus intensity, i.e., its perception threshold. If U is smaller than U_0, a sensation is absent. In other words, the ratio of the minimal increment in the stimulus strength responsible for the increment in sensation to initial stimulus is a logarithmic function. This line of reasoning gave rise purely phenomenologically to the Weber–Fechner psychophysiological law, which holds, however, only for moderate U and U_0 values. The spread of U and U_0 values somewhat compromised this elegant law. Coefficient α varied from one person to another. Certain authors criticized this quantitative perception theory.

Lazarev tried to resolve the dispute around the Weber–Fechner logarithmic law on the assumption that many people perceive the outside world by combining sensations detected by receptors of different sensory systems (e.g., visual and auditory). He sought to answer the question what happens if two stimuli arrive simultaneously via different receptor channels and therefore had to describe the behavior of function $\varphi(U, J)$ of sensation intensity E:

$$E = \varphi(U, J) \,, \tag{2}$$

where U is the intensity of a stimulus arriving, for example, via the visual reception pathway, and J is the intensity of an irritant coming through a different channel, e.g., the acoustic reception pathway. The report "Influence of Singing on Vision" (1918) [51] began with the following words: *I showed in preliminary papers published in 1905 that every time a sound irritates the organ of hearing, simultaneously with the irritation of the organ of vision, the sound seems to increase in strength. This means that if a constant sound is perceived simultaneously with flickering light, one gains an impression of beats so strong that the phenomenon can be demonstrated in the auditorium. It takes place only for loud sounds. Light-excited sensations cease to influence acoustic ones as sounds decay, and the influence of light on the sound becomes inverted, i.e., the sound seems weak in the light*. Then, Lazarev noted that these experimental data provide a basis for the law of mutual influence of light and sound. He tried to explain this phenomenon based on the provisions of his ion theory of excitation [20].

I do not reproduce here the description of Lazarev's experiments reported in [50, 51], since his article is available free on the Internet. Instead, I shall mention briefly his mathematical manipulations. However, a preliminary remark is in order.

Any mathematical model is built in accordance with the following scenario: "*If..., then...*". After "if" postulates of the model are enumerated. 'Then' is followed by analytical equations often supplemented now by computer simulation. Implications of these postulates are verified in experiment. No matter how elegantly the model is built, its consistency with reality is determined by its postulates and their experimental verification.

Lazarev suggested that the sound-light interplay in receptor systems is a nonlinear process. Taking logarithm of parameters obtained by generalizing the Weber–Fechner law in the logarithmic form allowed him to convert multiplication into addition for the case of interaction between two or more organs of senses:

$$E = \alpha \log U + \beta \log J + C \,, \tag{3}$$

where α, β are coefficients, C is an integration constant, U is the sound intensity, and J is the light intensity. Lazarev concluded: "This is the generalized Weber–Fechner law for the reciprocal influence of two organs of the senses."

Today, Lazarev's model described by expression (3) would seem obsolete in light of the data on the modes of information processing in the brain obtained for the past 50 years, because we use different languages, e.g., the language of information theory, unknown in the early 20th century, to interpret them. Section 8 gives an idea of the dynamic gain from the interaction between combinations of receptor systems during perception of environmental information.

To recall, expression (3) contains three parameters, α, β, and C, besides irritation intensities U and J measured in experiment. These parameters are unmeasured variables characteristic of each human being.

Our brain forms a virtual model of the environment including spatial mapping [52]. Any whole composed of parts or blocks is not their mechanical sum but the totality

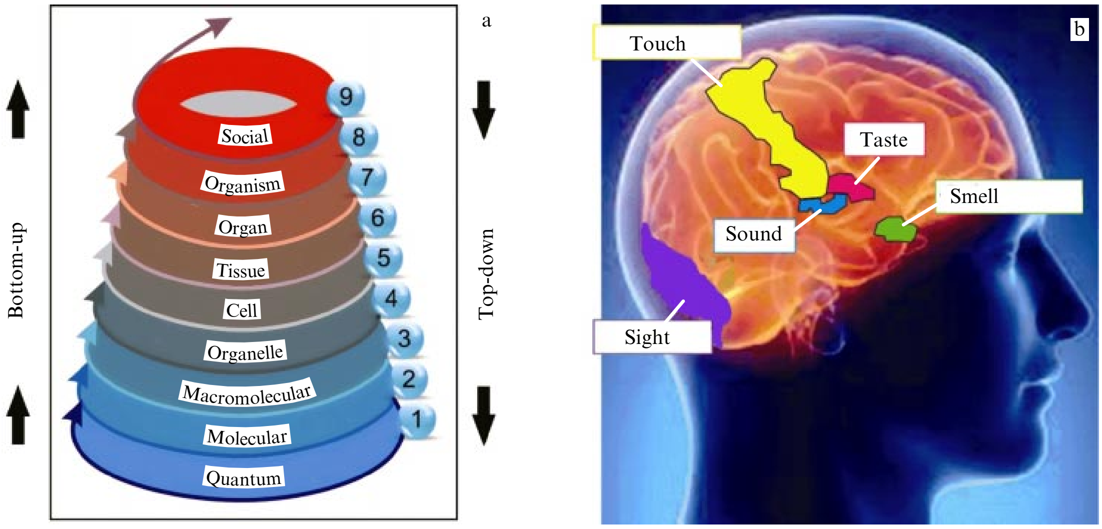

Figure 1. Hierarchical organization of living systems (a) [56] and nuclei representing different receptor systems receiving environmental information in the human brain (b).

of their actions [53, 54]. Each lower hierarchical level (Fig. 1a) is inserted into the next higher one that can be regarded as a whole with respect to all low levels [55].

The evolution of biological systems is the buildup of hierarchical levels (Fig. 1a) and the development of communication 'languages' at each of them. The 'chemical language' appeared during the early evolution of primitive systems to coordinate ongoing processes. It was becoming increasingly more complicated with the emergence of signal molecules produced by specialized cells that regulated the behavior of other cells in different parts of the system. The advent of nerve cells gave rise to the 'electrochemical language', i.e., long-range information transfer along axons by electric pulses (axons of adult humans can be as long as 1–1.5 m while being only 0.025 mm thick). Simultaneously, 'olfactory', 'acoustic', and other languages developed to facilitate communication between individuals. The earlier languages did not disappear but underwent modification and further sophistication, even though some of them were party reduced. Sensory and motor systems evolved in parallel with language formation. The development of the languages and means of information transfer occurred as a cyclic interaction process. The development of one system influenced the formation of another, either speeding it up or slowing it down.

Examination and modeling of each level without regard for the closest lower ones introduce uncertainty and do not allow elucidating in full measure the mechanism underlying the dynamic behavior of the integral system [57, 58]. The model described by expression (3) takes account of all these factors, although not completely.

Lazarev was right when he wrote in his article of 1918 [51, p. 1302]: "There is reason to think that it is not only these two organs of the senses that can mutually influence each other but that it is a common law for all organs of the senses; therefore, quantity C must depend on the degree of irritation of the remaining centers of sensations." In fact, Lazarev predicted two phenomena: first, the interaction of different receptors to solve any spatio-temporal problems; second, the relatively rare interaction of two or more sensory systems in the form of their partial or complete merging known as synesthesia (the term is from the Ancient Greek συναίσθηση — 'together' + αἴσθησις 'sensation'). This phenomenon is the limit variant of interaction between sensory systems in which two receptor channels become either synchronized or integrated into a single one. However, the question "where and how does synesthesia originate" remained unanswered at that time.

Table 1. Diversity of receptor system functions.

No.	Action	Description
1	Adaptation	Reduction (increase) in receptor system susceptibility upon increase (decrease) in external stimulus intensity
2	Sensibilization (desensibilization)	Increase (reduction) in sensitivity and resolving capacity of receptor systems by means of targeted daily workouts (receptor neurofitness)
3	Compensatory substitution	Ability of one receptor system to partly perform the function of another in the case of insufficient susceptibility of the latter (neuroplasticity of receptor systems)
4	Synesthesia	Unification of receptor channels resulting in the appearance of sensations in the brain characteristic of different types of reception. Unification occurs spontaneously regardless of person's desire. Synesthesia should be viewed not so much as a reception property but the property of analysis of information coming from receptors by the brain, i.e., recognition of images of the outside world (see Section 8)

Only at the end of the 20 century did it prove clear that a receptor-mediated sensation involves at least four functional variants of receptor systems perceiving environmental information (Table 1).

4. Discussions around synesthesia

4.1 Does synesthesia actually exist?

The existence of synesthesia has for a long time been questioned. It has been regarded as a pathological condition. In the English-language literature, the discovery of synesthesia is ascribed to F Galton, who became interested in this phenomenon in the late 19th century [59]. However, Galton was hardly the first to notice the influence of certain receptor channels on others. Professor S V Kravkov, a pupil and co-worker of P P Lazarev's, writes in his monograph [60]: "In the 17th century, the well-known Danish anatomist Thomasius Bartolinus described his observations of hard-of-hearing subjects who heard better in daylight than in the dark. In the late 18th century, Ebermayer and Horn undertook a special study and found that exposure of the head to light improves hearing in people presenting with ear diseases."

Synesthesia manifests itself not only when sounds automatically elicit conscious and reliable visual experiences (auditory-visual synesthesia or 'color hearing') but also when the perception of each of the numerals, e.g., from 0 to 9, or some letters is associated with the experience of colors (grapheme-color synesthesia). Later investigations revealed many various forms of synesthesia.

The most difficult step in any research is to substantiate the new phenomenon of interest, because its further examination and modeling make sense only when there is reliable evidence of its existence.

On the one hand, people with synesthesia were often unaware of their unusual capabilities, while others knew of them but preferred to keep them out of the public eye for fear of being recruited for scientific experiments or being unwilling to allow psychologists to intrude into their inner world.

On the other hand, most researchers were of the opinion that *synesthesia* is a result of self-persuasion or merely its metaphoric poetical name, such as 'loud colors', 'sweet sounds', 'sullen paints', 'brilliant violin playing', or 'sugary speech', rather than a real fact. It was believed that a person talking about his or her peculiar mode of perception of the outside world simply wants to be regarded as distinguished from all other people.

A major challenge is how a person can explain his perception of the outside world to another person with different sensory capabilities accounting for different perceptions. Animals are known to possess feelings that are absent or poorly developed in humans. This fact has for many years precluded the buildup of the 'evolutionary tree of receptor systems'. By way of example, sharks are capable of electroreception, allowing them to sense the electric fields of their prey. Certain bacteria make use of magnetoreception, which also forms the basis of navigation systems in birds and insects. The lateral line of fish provides a tool for echolocation that is most extensively exploited by bats. Insects, snakes, owls, and even deer rely on infrared vision for night-time feeding. The set of receptors depends on the ecological niche occupied by a given species. The world of a bee or an ant differs from that of a frog or dragonfly. Humans are likely to possess in the 'embryonic state' receptors inherent in other living organisms, but they manifest themselves only when the main receptor systems fail to operate adequately.

Cell division can cause mutations [61]. All of us specifically perceive the outside world. Our body, receptor systems, and brain are a mosaic of cells differing from one another as confirmed by genome-wide sequencing [62, 63].

Of special interest is that if most people have some kind of perception, and some do not have it, then this absence is easy to detect. For example, most people are able to recognize colors in the visible wavelength range (Table 2), but some lack one of the three types of cones in their retina; such people are unable to distinguish between colors. Daltonism or color blindness is readily diagnosed using polychromatic tables [64].

Table 2. Electromagnetic wave length and color perceived by living organisms with normal vision.

Range of vision in certain organisms, nm	Wavelength, nm					
	300 – 350	350 – 400	400 – 450	450 – 500	500 – 550	550 – 600
Bee $\leqslant 300$	+	+	+	+	+	+
Frog 432 – 574	–	–	+	+	+	+
Turtle 442 – 562	–	–	+	+	+	+
Pigeon 500 – 562	–	–	–	–	+	+
Monkey 440 – 630	–	–	–	+	+	+
Human 440 – 630	–	–	–	+	+	+
Wavelengths perceived by three types of cones in human retina						
Type of cones	Notations	Wavelengths perceived, nm			Maximum sensitivity corresponds to	
S	β	400 – 500			420 – 440 nm	
M	γ	450 – 630			534 – 550 nm	
L	ρ	500 – 700			564 – 580 nm	
Colors normally perceived by humans, their respective wavelengths (nm) and photon energies						
Wavelengths, nm	$\leqslant 450$	430 – 510	510 – 550	550 – 590	590 – 630	$\geqslant 630$
Colors perceived by brain	Violet	Blue	Green	Yellow	Orange	Red
Photon energy, eV	$\geqslant 2.75$	2.75 – 2.43	2.43 – 2.25	2.25 – 2.17	2.17 – 1.97	$\leqslant 1.97$
Wavelength ranges are approximate, since colors transit smoothly from one to another; visible boundaries between them mostly depend on observation conditions [65].						

With the phenomenon of synesthesia, the situation is reversed. Synesthesia is absent in the majority of people and occurs only in a small group of them.[9] This phenomenon is difficult to identify. For example, it is hardly possible to explain to a congenitally blind person how one with normal vision sees the outside world. They will not understand it because they live in a different world that is perceived by the sense of touch, hearing, and smell.

The existence of synesthesia was suspected long ago but it was usually regarded as a curious incident unworthy of scientific consideration. For this reason, physicians usually misinterpreted synesthesia as schizophrenia and prescribed neuroleptics to prevent hallucinations. Even now, the existence of synesthesia as a normal physiological process is doubted by many specialists [66].

4.2 How we perceive sounds

Normal perception of light and sound (Table 3) occurs without manifestations of synesthesia.

The human ear usually hears sounds in the wavelength range from 16 to 20 kHz, although some people can hear 8 Hz infrasound. I encountered a case of unusual perception of infrasounds in the 1960s. It turned out later to be only indirectly related to synesthesia.

Consideration of the mechanical vibration scale, from ultrasound to infrasound, reveals uncertainty. Irregular infrasound can originate from eddies of air flows around any obstacle. It is safe to maintain that sound perception is not confined to the ear transmission band. Infrasounds are known to influence human beings, even if we do not hear them. For example, it happened that certain passengers in an old trolleybus did not hear the noise of the air-brake compressor but experienced pain in the ears when it operated.

Turning back to the work of biophysicists from P P Lazarev's school, it is worth noting their research on infrasounds generated by strong winds over the sea surface as a result of vortex formation behind the wave crest. Such a 'sea voice' (a sign of an approaching storm) was investigated by Academician V V Shuleikin and co-workers [67] (see preceding section), who discovered it from vibrations of a balloon surface. The researchers noticed that vibrations (compression $\leftrightarrow$ expansion) of an elastic balloon placed close to the ear transmitted changes in pressure to the tympanic membrane and sometimes caused acute pain. Shuleikin designed a microbarograph to measure the intensity and frequency of pressure variations and showed that the frequency of infrasound vibrations varied from 0.1 to 6 Hz and pressure from 1 dyne cm^{-2} or 1 μbar to several ubars (which corresponds to a sound pressure of 75–85 dB).

Table 3. Sound perception in certain mammals.

Species	Receptor	Function	Reception bandwidth, Hz
Bat	Ear	Ultrasound echolocation and communication	$40 \times 10^3 - 100 \times 10^3$
Domestic cat	Ear	Orientation and communication	$\leqslant 50 \times 10^3$
Dog	Ear	Orientation and communication	$\leqslant 45 \times 10^3$
Human	Ear	Orientation and communication	from 16 to 20×10^3
	Skull bone vibration		220×10^3

'Sea voice' infrasound propagates in the air at a speed of ~ 330 m s^{-1}, while the velocity of longitudinal-transverse shear sea waves in the process of their swirling depends on the wind force acting on the water surface and elasticity-to-density ratios of the air and water. Therefore, infrasound waves in the air move faster than storm waves in water, which permits us to predict an approaching storm. Today, the prognostic value of such investigations for marine navigation is diminished owing to the capability of space probing the entire water surface of Earth.

Due to the low oscillation frequency of infrasound at the same energy as that of perceived sound, it has a wide amplitude range. In accordance with the Huygens principle, infrasound easily passes round small obstacles and can induce resonance phenomena resulting in serious damage to large objects. Finally, it propagates over long distances by virtue of its low absorption in the atmosphere. These properties make it difficult to fight infrasound, because conventional noise reduction methods (sound absorption and insulation or withdrawal from the source of noise) are inefficient. Infrasound can induce a subconscious feeling of fear in humans, depending on its strength. A 4–7-Hz infrasound is known to cause seizures in epilepsy-prone subjects. An enhanced intensity of infrasound may be a cause of somatic disorders, including acute visual deterioration and injury to the inner structures of the ear.

The frequency of 4–7 Hz corresponds to the borderline between delta (0.54 Hz) and theta (5–7 Hz) rhythms recorded on human electroencephalograms (EEGs). It is known that theta rhythm originates in the frontal lobe of the brain in a state of emotional strain associated with the search for an optimal behavior under unusual external conditions in a memory engram[10] based on a previous experience. To recall, delta-rhythm occurs in all brain regions during natural or drug-induced sleep. Therefore, it can be supposed that 4–7 Hz infrasound causes in humans a specific emotional state associated with the formation of a bright but virtually unconscious image of integration of internal and external media into a united whole. As is shown below, this often causes uncertainty, giving rise, for example, to a feeling of fear.

In 1961, a book overviewing the work of the American physicist Robert Wood [68] happened to catch my eye. Chapter 19 describes the following situation: *John Bolderstone rehearsed a play at the Lyric Theater in which the setting had to be switched from our days to 1783 while fading out the scene. Wood was asked to think how to make such a leap psychologically and emotionally convincing. The idea of Wood was that a very low note, almost unheard but making the tympanic membrane vibrate, would evoke a feeling of mystery in the audience and create a proper mood in spectators. The note was generated using a 'superpipe' longer and thicker than church organ pipes. It was decided to test the pipe during the rehearsal. Only Wood, Lesly Howard, Bolderstone, and*

[9] By various estimates, the number of synesthetes in the general populations ranges from 2% to 12% [60].

[10] Engram (from Greek ἐν-in + γάμμα — letter). The term was coined in the 20th century to designate the memory trace in the brain left by a preceding stimulus.

D Miller, stage director, knew what awaits those present in the hall. A cry from the dimmed scene marked a 145 year break. Effect that followed right after Wood's 'unheard' note sounded was akin to an earthquake. Chandeliers of the old Lyric Theater jingled, window glass rattled, and the entire building trembled. A wave of horror spread over the Sheftsbury Avenue. Miller ordered the 'so-and-so' pipe to be immediately thrown out. Infrasound radiation provoked panic among the viewers; they all rushed to the doors.

In 1965, I decided to reproduce this effect in miniature. I assembled a small device consisting of a low-frequency optical-mechanical generator producing electric voltage of any amplitude and low frequency (0.01–15 Hz) [69]. The voltage was fed to an electromagnet coil that moved a cardboard fan to induce air vibrations in the infrasound wavelength range. The experiment showed that the device produced wind that caused unpleasant sensations at certain frequencies. As the frequency approached 15 Hz, a noise resembling the howl of the wind or a roar was becoming audible, but it caused neither a sense of fear nor panic in the observers. It was clear that the fear-driven panic behavior described in the preceding paragraph was due not to the ultrasound itself but to the absence of knowledge about its hidden source. If people see the source of infrasound and feel safe, the infrasound does not scare them, because the brain has to make resort to a probabilistic logic under conditions of uncertainty and seeks to take overcautious decisions to avoid dangerous situations [56].

In the summer 1966, a group of participants of the II International Biophysical Congress, including myself, attended an organ concert in St. Stephen's Cathedral, Vienna, one of the largest in Europe. The music that played under the cathedral's vaults produced an unusual effect on me and some of my colleagues. The polyphonic fugue voices with their bass tones wrapped about the body made the skin creep and hair on the head stand up. Taken together, these vibrating sounds now tightened then relaxed some heart-strings, while parallel melodic lines fused into harmonic compositions that brought back memories of the dear but forgotten past related to the innate primary perception of the world [70].

Infrasounds at 5–7 Hz cause anxious feelings. Modulations of the air leaking through large organ pipes, the so-called vibrato, can produce infrasounds. The acoustic properties of the cathedral can serve as low frequency resonators. The resultant effect may be due not only to the influence on the organs of hearing but also to vibrations perceived by the skin.

Such were my thoughts 50 years ago; I was then a young biophysicist. Now, I have begun to understand that those impressions arose not so much from hearing music as from the entire situation and the novelty of all that was happening. The colors of giant stained-glass windows, the walls impregnated with the scents of spiritual smoke, the spacious interior of the church, the darkness of its cupola, the contrast lighting of the mourning sculptural groups taken out from the darkness, the coolness of the vaulted arcades, silent people waiting for a miracle to come — all these created the mystical mood and inimitable atmosphere of the mystery of art. It was perceived not only by the basic sense organs known yet to Aristotle but also by others directed inwardly and responsible for the feelings of space and volume, expectation and curiosity, rhythm and time, happiness and grief. Biophysical mechanisms behind combinations of these feelings remain poorly studied, but they supplement those underlying the five main ones. The totality of them form the emotional state of humans. In such an environment under the influence of music, we create by ourselves a virtual model of the outworld by extracting certain episodes from our memory, combining and interpreting them in a manner that seems unnatural in the framework of a substantive-logical cognitive scheme.

Clearly, the image (pattern) of the external medium in brain research must be formed based on a combination of different receptor modalities. Pair combinations of sensory perceptions leave open the possibility of

$$C_5^2 = \frac{5\times4\times3\times2\times1}{2} = 60 \text{ different combinations.} \tag{4}$$

Different combinations of interaction between receptor systems into two, sometimes three, groups are probably possible during information perception:

$$\langle C_5^2, C_5^3, C_5^4, 1\rangle = \langle 60, 20, 5, 1\rangle\,. \tag{5}$$

Exceptions do occur. In 1968, the outstanding Russian neuropsychologist A R Luriya published a brochure about S V Shereshevsky, also known simply as patient Sh. [71]. He was the subject of Luriya's case study over a thirty-year time span. The memory of this man was unique in terms of the number of combined receptor systems. He thought in images, almost to the exclusion of other kinds of thinking. For him, digits, words, and music each had a specific color, taste, and smell. Luriya writes: "The entire world of his was different than that of ourselves. He knew no boundaries between colors, sounds, senses of taste and touch.... Smooth and cold sounds as well as rough colors, salty dyes, and bright, light, or prickly smells... all of them were entangled and mixed so that it was impossible to distinguish between them...." Luria diagnosed in Solomon Shereshevsky an extremely rare version of synesthesia, fivefold (quintuple) synesthesia. The man perceived both texts and separate words as associated not only with bright visual-spatial images but also as having sounds, taste, colors, and shape. Shereshevsky could remember infinite sequences of names or recall word by word talks that he had heard; they turned in his brain into fantastic images alternating their form like that of plants, people, or buildings. At the same time, Shereshevsky experienced great difficulties in understanding abstract concepts. The ability to automatically and almost infinitely long keep in memory every minute detail interfered with the capacity for understanding and generalizing.

To sum up, a pattern of the external medium is formed from any combination of external signals entering the brain through different receptor systems as a result of the coupling of 2 to 5 receptor channels. For example, a cat is woolly (touching), purrs and meows (hearing), has a physical appearance (vision), and has a specific smell (olfaction). These properties generalized in our brain form the image of what we call 'cat'.

Aristotle distinguished five main sensory systems in humankind supplemented by a variety of others formed by specialized receptors such as receptors of warmth or its absence on the skin (*thermoreception*), receptors of equilibrium (*equilibrioception*), pain receptors in the skin, joints, and other organs (*nociception*), and even receptors responsible for the perception or awareness of the position and movements of the body (*proprioception*). Some researchers count at least 20 types of receptors, including many poly-

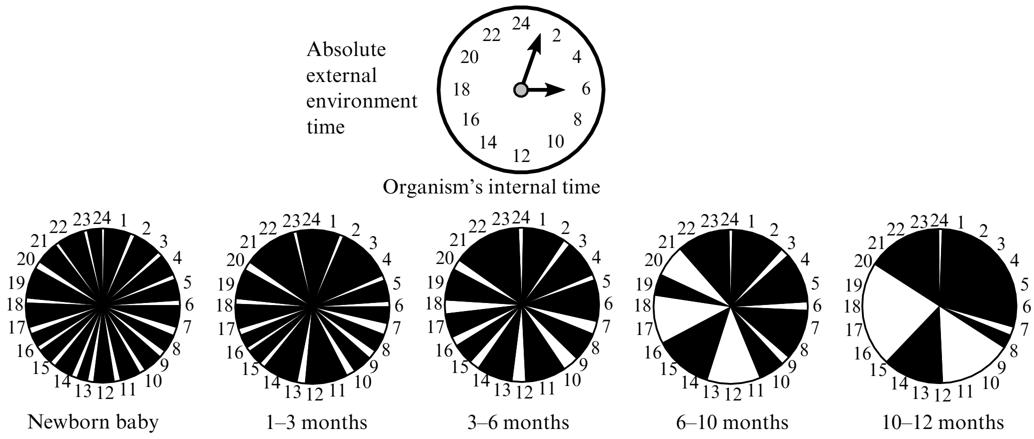

Figure 2. Variations in wakefulness (light intervals) and sleep (dark intervals) rhythms during early human ontogenesis.

modal ones in which a single nerve ending can be excited in response to a few different stimuli [72].

4.3 Perception of external situations: reception coupled with emotions

I have recently read I A Bunin's story "Chung's dreams", recounting feelings of a dog called Chung that happened to be in a church during a funeral service held to memorialize its deceased master. Here is an extract from the story: *Suddenly the door swings open and a wonderful reverberant singing picture pierces Chung's eyes and heart*: *he sees the dim gothic chamber, red stars of lights, the greenwood of tropical plants, the oak coffin placed high on the black scaffold, the black crowd of parishioners, and two women in deep mourning beautiful as marble sculptures, like two sisters of different age*; *he hears the hubbub of voices, thunders, the clergy calling out loudly to angels in a sorrowful joy, glory, confusion, splendor, and unearthly chanting spread over the whole length of the church. And up goes his hair from pain and delight over this sounding vision....*

Of course, Ivan Bunin could not slip into the dog's skin. He merely described his own feelings in such a situation, as appears from the very first sentence of the story: "*Does it matter who to talk about? Everyone on earth deserves it*."

Thus, each person perceives the outside world and various situations it offers as a whole by combining information that comes through different sensory channels and superposing it on his or her memory engram. Such perception is the precursor of synesthesia. Here is one more example.

4.4 In the world of rhythms — does the "Mozart effect" work?

In 1999, *Nature* published a discussion between two groups of psychologists under the intriguing title "Prelude or Requiem for the 'Mozart Effect'" [73–75]. The discussion arose in connection with the assertion of psychologist F H Rauscher that college students hearing bravura music (passages of Mozart's Sonata for Two Pianos in D major, K 448) during a 10 min break improved their IQ. [11] The improvement was slight (8–9 points) but allegedly significant. A different manner of 10 min relaxation in silence was chosen as a control.

The paper by Rauscher appeared in *Nature* [76] in 1993. A group of specialists (Kenneth M Steele, Simone Dalla Bella, Isabelle Peretz, et al.) from three Canadian universities published in response their own article [74] in which they reported the reproduction of Rauscher's experiment that failed to reveal a direct effect of music on intellectual abilities. The 8–9 point rise in IQ was shown to be within the natural spread.

The article by the Canadian authors was followed by comments by Rauscher published in the same journal [75]. He argued that hearing does not necessarily affect intellectual capability as a whole but can improve the ability to solve spatial-temporal problems, including operations with mental images and their sequence order in time. In other words, Mozart's rhythmic sonata changed the internal time function of mental processes.

I consider this conclusion to be self-evident for two reasons. First, the biological time scale is highly flexible and subject to variations in a wide range. All living systems can not be Galilean systems, because they develop and undergo modification under varying environmental conditions. Therefore, an information carrier can not move inside the brain at a constant speed. Galilean transformation is based on the principle of relativity suggesting identity of time in all reference frames, i.e., external absolute time. The brain works within its own internal biological time scale.

The scale of internal biological time variations is well known [77]. In living systems at all levels in spatio-temporal coordinates, alternation of acceleration (activity) and deceleration (relaxation) always takes places. Here is a trivial example of variations in the characteristic time scale in early human ontogenesis. A child is born with its own time scale confined, at the beginning, to the primitive division of the 24-hour period of day and night into alternating episodes of food intake, sleep, and discharge of bowel contents. The situation changes within the next month. The intervals between the episodes gradually become longer and adapted to the diurnal rhythm (Fig. 2).

Plasticity of adaptation of the internal time scale to the external time scale is preserved across the human life span. P P Lazarev and co-workers demonstrated different adaptation scales altering with age and diurnal and seasonal variations in the environmental conditions, as exemplified by those in the visual system [44] (Fig. 3).

[11] IQ (*intelligence quotient*) is a measure of intelligence. The average IQ score in adults is $\approx 100 \pm 15$, although some people have IQ $\gg 100$. It was shown that IQ depends on both heredity and living environment, including education, parenting practices, and surrounding mental atmosphere. As modern society evolved over the 20th century, a long-sustained increase in IQ scores was measured in many parts of the world at the average rate of three IQ points per decade (Flynn effect).

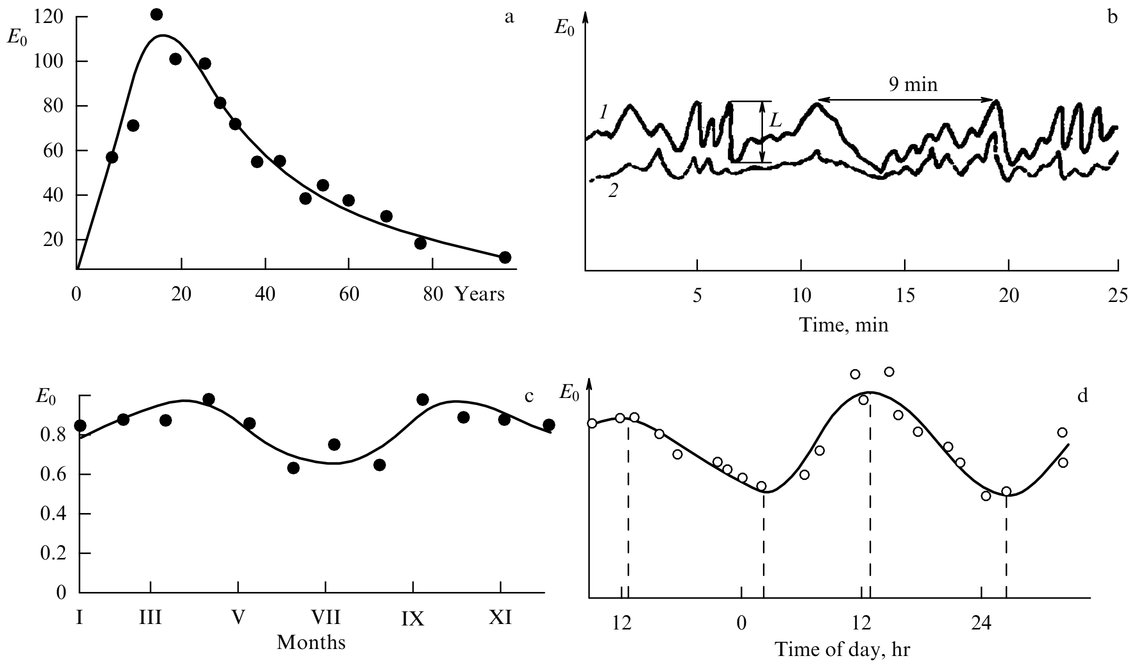

Figure 3. Variation in threshold visual sensitivity U_0 during dark adaptation: (a) changes in threshold sensitivity with age, (b) examples of characteristic records of threshold sensitivity variations in two test subjects at a rapid time scale, (c) seasonal variations in threshold sensitivity apparent from monthly averaging, (d) diurnal variations in threshold sensitivity manifested upon hourly averaging [44].

In a Galilean system, the body speed with respect to a stationary system of coordinates equals the vector sum of the body speed relative to a moving system of coordinates and the speed of the moving system. In this case, vector summation of the speeds, both mean and instantaneous, takes place:

$$\mathbf{v} = \mathbf{v}_0 + \mathbf{v}^* , \tag{6}$$

where $\mathbf{v}$ is the relative mean speed of the body with respect to system K, $\mathbf{v}^*$ is the relative mean speed of the body with respect to system K$'$, and $\mathbf{v}_0$ is the relative average speed of system K$'$ with respect to system K. For the purpose of the description of living systems, Galileo's expression $\mathbf{x} = \mathbf{v}t$ at $|\mathbf{v}| = \text{const}$ for path $\mathbf{x}$ should be substituted by Newton's expression with accelerations and decelerations ($\pm\mathbf{a}$), i.e.,

$$\mathbf{v} = \mathbf{v}_0 + \mathbf{a}t . \tag{7}$$

In this case, acceleration $\mathbf{a} = \mathbf{v}_1/\tau$, where τ is the characteristic internal time, specific for each organ and organism. Each brain region has its own characteristic internal time manifested in EEG rhythms. Regulation of the process rate inside an organism, including the process of thinking, is apparent as changes in the characteristic time scale. In the general case, the expression for τ takes the form

$$\tau = \left(\frac{\mathbf{v}_1}{\mathbf{v} - \mathbf{v}_0}\right) t . \tag{8}$$

Let us use the notation $k = \mathbf{v}_1/(\mathbf{v} - \mathbf{v}_0)$. Then,

(1) if $k > 1$ increases, characteristic time τ increases too, which corresponds to deceleration;

(2) if $k \in \langle 0, 1\rangle$ and tends to vanish, characteristic time τ decreases, which corresponds to acceleration.

(3) if $k = 1$, characteristic time τ is synchronized with external time, and the system turns into a Galilean system.

Differentiation of k and finding the extremum yield the condition for synchronizing the internal system of the organism with the ambient environment. It corresponds to the equality

$$\frac{\mathbf{v}_1}{\mathrm{d}\mathbf{v}_1} = \frac{\mathbf{v} - \mathbf{v}_0}{\mathrm{d}(\mathbf{v} - \mathbf{v}_0)} . \tag{9}$$

It follows from the above that the characteristic time of the organism can be compressed or expanded by the feedback mechanism; if a compromise is reached, it coincides with external time. Process deployment time in the virtual model inside the brain changes along the astronomical time axis from childhood to old age, but we can notice it only by comparing it with something immobile, to be precise with the memory of the past. Large periods of the past are noticeable, for example, from the altered appearances of ourselves in old photographs. Short time intervals are characteristic of alteration of neuronal network rhythms in the brain (see Section 8).

Imposition of a rhythm in the linear approximation can be regarded as a 'game' in terms of positive and negative links; with localized masses in the simplest case it can be described by a second-order differential equation with the right-hand side in the form

$$m\ddot{x} + b\dot{x} + kx = F(v_0 - \dot{x}) , \tag{10}$$

where the external medium changing at the rate v_0 affects the motion of information carriers with mass m inside brain structures moving with alternating deceleration and acceleration k_1 and k_2 both near equilibrium and far from it. The resulting interaction coefficient is denoted here by k.

The equilibrium point x is displaced with speed $\dot{x}$. The friction force affecting mass displacement near the equilibrium point is taken as the function $F(v_0 - \dot{x})$. The solution of this equation for the case of periodic coupling of internal processes with external ones has been known since long ago [78]. It yields a parabolic phase portrait called a 'saddle' and thus demonstrates unstable equilibrium. Feedback loops are a key feature of any adaptive system. Such mathematical interpretation can be applied with certain limitations to the description of brain processes [79]. The mechanical point analog of such an interaction can be, for example, a Froude pendulum oscillating on a rotating shaft [80]. In this metaphor, the pendulum is an analog of the biological system, while the independently rotating shaft corresponds to the external medium. Such a pendulum is one of the simplest mechanical auto-oscillating systems. The angular velocity of the shaft can be higher than that of the pendulum. Therefore, the moment of friction acting on the pendulum slows down the movement during one half period when the pendulum and the shaft are moving in different directions and speeds it up during the other half period when the pendulum and the shaft are moving in the same direction. This gives rise to asymmetry in the movement created by negative friction [81].

Therefore, if the force of friction asymmetrically changes sign, the accelerating torque is on the average greater than the decelerating one, leading to an increase (self-excitation) in oscillations; as a result, auto-oscillations can develop in a point system [80] and auto-waves in a distributed one, if conditions permit [82]. When energy is fed into a pendulum system with a low Q-factor, it can considerably change the character of ongoing processes, and the shape of oscillation becomes different than sinusoidal. Any pendulum in which friction forces are compensated for by the energy coming from the outside can be considered in terms of a 'predator-prey' relationship, because the prey had to adapt itself, to survive in the course of evolution, to the rhythm (including a change of motion) imposed by the predator (external factor) [83].

In human society, motion activity rhythms imposed by external ones have been employed since long ago as exemplified by marches performed by brass bands, military drum rolls, rhythmic dances, tedious work done to a rhythmic tune, etc.

However, the psychophysical observations described above do not give convincing evidence of synesthesia, they only show that the perception of the outside world occurs via a combination of pieces of information coming from all sensory systems of the organism and its internal state.

P P Lazarev intuitively postulated that the interactivity of receptors is a normal physiological sensing process; therefore, it is necessary not only to state the fact of the influence of rhythms on sensory capabilities, but also to consider it as one of the stimuli contributing to the formation of links between different receptor systems [43].

5. Weight of each perception in the image recognition of the outside world

5.1 Visual reception

In many animals, including humans, the system analyzing optical information plays a key role. It has at least 6 levels, because the retina is actually a peripheral fragment of the brain. Human beings receive up to 7/8 of the information about the outside world from the visual system. There is reason why P P Lazarev and his disciples sought to discover

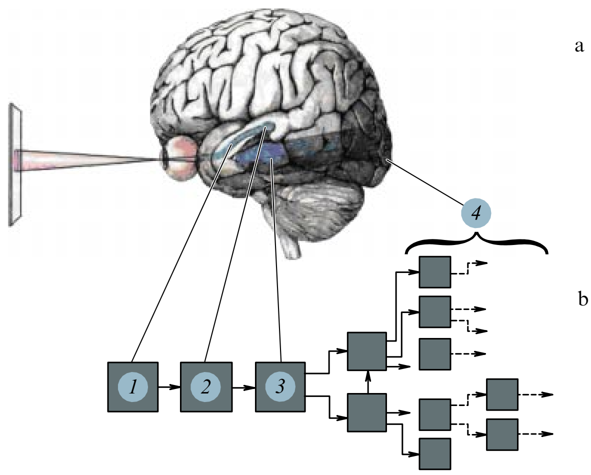

Figure 4. Anatomy of the optic tract (a) and its simplified flow diagram (b): *1* — optic tract from the retina to the lateral geniculate body (*2*), *3* — visual radiation (a uniform distribution of the bundle of nerve fibers over the area of the subcortical zone with striatal subsections[12]), *4* — visual representation area in the higher cortical regions.

the secret of brain work by focusing on information processing in the visual receptor channel. Figure 4 shows visual information pathways from the retina to the occipital brain region [84].

Peculiarities of information treatment in the brain based on visual reception were known before the advent of magnetic resonance imaging (MRI), which permits us to observe the dynamics of brain processes, even if with a rather low resolution.

In Russia, visual reception was explored in the Laboratory of Vision Biophysics headed by Prof. N D Nyuberg (1899–1967). Up to 1963, the laboratory was based in Moscow as a division of our Institute of Biological Physics, USSR Academy of Sciences. After the institute moved to Pushchino, the laboratory joined the Institute for Information Transmission Problems. The history of this laboratory can be traced to P P Lazarev's institute, and the studies it carried out originated from the research conducted by S V Kravkov (1893–1951), who greatly contributed to the psychophysiology of the sense organs. He occupied for some time the position of senior assistant at the Institute of Biophysics headed by P P Lazarev. Guided by Lazarev, Kravkov showed that humans have a unique ability to keep attention focused on the most important features of the subject of interest while disregarding inessential ones, despite changes undergone by the brain processing visual stimuli.

In the same laboratory, A L Yarbus (1914–1986) registered eye movements using special suction cups attached to the eyeball. This allowed recording and assessment of eyeball motions when viewing various scenes. He summarized these observations in the book *Eye Movements and Vision*, published in 1965 and translated into English [85]. Even today, after more than 50 years have elapsed, the book is read with great interest. All appears to depend on the time limit for addressing the problem in question. Let us consider

[12] The visual cortex includes the primary visual cortex, also known as the striate visual cortex or visual area VI and extrastriate visual cortex (visual areas V2, V3, V4, and V5). The primary visual cortex is the anatomical equivalent of Brodmann area 17 or BA17. The extrastriate visual cortex includes Brodmann areas 18 and 19.

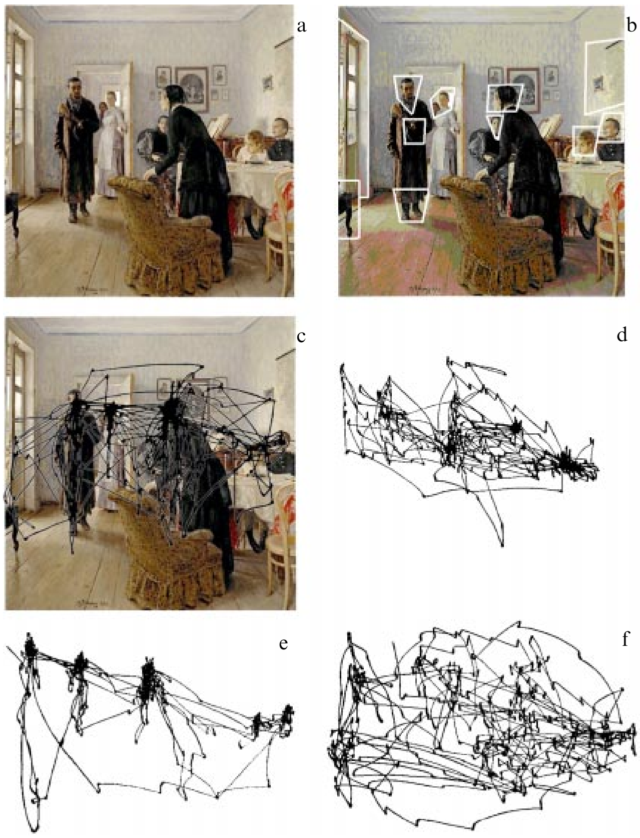

Figure 5. Example from the book by A L Yarbus, *Eye Movements and Vision* [85]: (a) I E Repin's painting "An Unexpected Visitor", (b) its breakdown into parts, i.e., information elements, to solve the problem under consideration, (c) eye movement trajectories over a short (3 min) examination of the picture for remembering its subject, (d) eye movements during examination to guess what the family was doing prior to the arrival of the unexpected visitor, (e) eye movements during examination for determining the age of the characters in the painting, (f) eye movements during examination for determining positions of the characters and objects in the room. Evidently, trajectories of eye movements for identifying the parts of interest depend on the problem posed [85].

the importance of the goal-setting process for recognizing the outside world picture (Fig. 5) to identify the features most essential for the solution to the problem.

5.2 Transition from fragments to assembly of a whole

The brain on an unconscious level breaks down observed images of the outside world into fragments to identify the most informative ones but then integrates them into a whole with reference to the arising problem. Each fragment is given a certain weight, depending on the problem to be solved.

At present MRI makes it possible to reveal excited brain regions under different information loading. Specifically, it was shown that the V4 part of the brain contains a region in the lateral occipitotemporal gyrus responsible for operations with numerals, because damage, e.g., in the case of stroke, makes people incapable of arithmetic calculations and may lead to digit-color synesthesia.

Thus, the process of visual perception starts at the moment when nerve impulses are sent from the retina to the posterior part of the brain. Trains of such impulses serve as a code for a fragmented visual image. They carry information about color, movement, shape, depth, and perspective. This information is differentiated into signs characterizing different properties of the image and distributed among several areas in the temporal and parietal brain regions.

This means that enhanced cross-linking between neuron networks in the V4 zone may give rise to cross-links underlying the formation of digit-color synesthesia. What is it: a pathology or a genetically determined variant of perception?

The Oxford Handbook of Synesthesia published in 2013 [86] describes synesthesia as an interesting phenomenon that has enthralled the imagination of scientists and artists. Synesthesia is a condition inherited from the parents characterized by a sort of 'conversion of feelings'. In synesthetes, daily routines, such as reading or listening to music, are associated with unordinary impressions of color, taste, smell, and shape of objects or other unifying sensations. The study of synesthesia gives us, inter alia, the idea of normal feelings, because all people experience implicitly cross-sensory (synesthetic) representations. Synesthesia has great cognitive value, and recent decades have witnessed a rising tide of interest in this phenomenon. The knowledge of its manifestations promotes the development of genetics, psychology, history, aesthetics, and the entire spectrum of neurosciences by offering a source of problems to be solved by the new generation of researchers.

The Oxford Handbook predicts the emergence of new research areas related to synesthesia, including the evolution of languages, creative activities, and abilities to remember large volumes of information.

6. Proof of synesthesia

6.1 Late 20th century: variants of synesthesia discovered

The American psychologist V S Ramachandran described in his book *The Tell-Tale Brain: A Neuroscientist's Quest for What Makes Us Human* [66] experiments that allowed him to prove the existence of synesthesia. He lectured on the possibility of synesthesia and asked his students with this condition or who know other people with it to visit him. Observations of those who responded to the call are described below (Table 4).

6.2 21st century: extended studies of synesthetes

Synesthesia is considered in numerous articles [88–97] and monographs [98–102]. People interested in the nature of this phenomenon in different countries unite into groups and societies. One of them in Russia has built its own website (synaesthesia.ru). Synesthetes are actively sought by interested researchers. International congresses on synesthesia and its influence on the development of science and art have been organized on a regular basis in Spain since 2005. VI International Congress on Synesthesia, Science & Art was held on May 18–21, 2018.

To recall, a special research area concerned with the relationship between synesthesia and art has a long history. I confine myself to presenting three examples of synesthesia in my compatriots. The Russian artist V V Kandinsky, a founder of the doctrine of abstract painting, is believed to possess the synesthesia four receptor channels in the brain (color, hearing, tactility, and smell) [101, 102]. The American writer, poet, translator, literary critic, and entomologist Vladimir Vladimirovich Nabokov (a Russian immigrant) described synesthesia in himself (blue graphemes) (see 'Speak, Memory: Autobiography') [103] and in some of his literary characters. The third person is N A Rimsky-Korsa-

Table 4. Variants of synesthesia described by V S Ramachandran [66].

No.	Sex	Sensations and feelings as described by the patient	Ways of checking patients' reports
1	F	I always see digits in colors even if they are printed in black; for example, figure 7 is red for me. It makes it easier to remember telephone numbers since each digit seems to be specifically colored.	The patient was free from neurological disorders. Ramachandran drew the Roman numeral VII and asked the patient what she sees. The answer was: "I see seven but it looks black not red." Then, Ramachandran asked the patient to close her eyes, drew a 7 on her palm, and said: "I drew seven. Is it colored?" "The answer was "No. I can not see red color even if I 'feel' that it is 7. But when I visually imagine numeral 7, I see it as red." The color of each digit was constant, but different digits had different colors linked to their shape. Moreover, the patient, looking at a two-digit number composed of different digits, all the same saw each of them colored specifically. As the digits were written closer to each other, the patient reported competition between the colors that became dull. If 7 initially perceived as red was rewritten in green, the patient simultaneously saw two colors, green and red, that looked 'disgusting'. In the end, it became clear that digits seemed colored only after the patient perceived their meaning.
2	F	I always see digits and letters of the alphabet in colors.	The patient was free from neurological disorders. Ramachandran repeated the above tests and received the same answers with minor variations. The patient saw colored digits, but they were colored differently: 7 was blue and 5 green. She saw brightly colored letters. Neither Roman numerals nor digits written on her palm evoked any response. In other words, color sensations originated from visual imagination of digit shape rather than from the idea of the digit itself.
3	F	When I am playing piano, I hear sounds of different color, e.g. C sharp is blue. Each note has its peculiar color.	The patient was free from neurological disorders. Ramachandran did not obtain convincing evidence of the influence of sound on color sensations.
4	F	Touching some rough surfaces causes in me an emotional reaction, such as fear, alarm or disappointment while touching other materials causes the feeling of warmth and relaxation.	Ramachandran verified the presence of tactile-emotion synesthesia by recording microscopic sweat discharge and variation of skin electric conductivity (one of the parameters used in a polygraph). He ruled out dissimulation on the grounds that the character of emotions was consistent with perspiration patterns.
5	M	I see a colored halo around the face of all people, but it has different color in each person. The color becomes more intense and spreads over the entire face if I drink alcohol.	Ramachandran and his assistants showed the patient a photograph of a student from a different college, asked him to stare closely at his nose, and say what color halo he saw around the face. The answer was: 'red'. Then, different parts of the halo were exposed to rapidly alternating green and red point flashes; simultaneously, changes in the direction of the patient's glances were recorded. The patient reacted first and foremost to green points and only rarely to red ones. According to him, he did not see red points at all. It suggested that the patient actually saw halos because green points are noticeable against a red background while red ones are virtually invisible. The patient presented with an autism-related intellectual handicap (Asperger's syndrome). He encountered difficulties in understanding other people and 'reading out' their emotions. Intellectual conclusions from the context were needed rather than intuition as in the majority of people. Each emotion seemed colored to the patient, e.g., anger was blue and pride red. His parents had taught him from early childhood to have his own emotion evaluation system based on the recognition of these colors. Interestingly, when they chose to present themselves to the child 'with a lofty face', they described it as being a violet color (known to be a mixture of red and blue). The former corresponded to 'pride' and the latter to 'haughtiness' on the patient's color scale. He did not understand these parallels and his subjective color spectrum corresponded to the 'spectrum' of social emotions.
Ramachamdran's conclusion: Synesthesia exists. Violation of the standard receptor perception inherent in humans is associated with emotions and can also occur during learning. Apparently, this is an echo of the past in the history of the emergence of hominids. Color vision in primates and, in particular, hominids, was necessary for their survival. The combination of color with emotions at the neural level made it possible to distinguish between rip fruits and/or young leaves and shoots, to detect hidden predators agains the backgroound of greenery, and to remember the color features of the landscape. In the brain, these effects arose as a result of the interaction of the island of Reil and the higher parts of the brain responsible for color. If such combinations are excessive and perhaps a little confused in the brain, then this explains why color combine with emotions.			

kov, the famous Russian composer, pedagogue, conductor, and musical critic, the composer of 15 operas, 3 symphonies, and many instrumental compositions. He said in one interview that he had 'color hearing' [104].

The American winner of the Nobel Prize for Physics Richard Feynman described color symbols in mathematical equations: "When I look at equations, I see letters in colors though I have no idea why. When I speak, I see the obscure images of Bessel functions from the book of Yankee and Emde with flying light-brown j, bluish-violet n, and dark-brown x" (see Chapter "It's as simple as One, Two, Three..." in his autobiography *What Do You Care What Other People Think?* translated into Russian [105, pp. 40 and 51 in the English and Russian text, respectively]).

However, all these examples should be taken into account with caution, since they have never been the subject matter of objective research.

It was mentioned above that variants of synesthesia are numerous. For example, there is a documented case of tactile contacts coupled with emotions that caused a gustatory sensation. Rubbing an iron mesh fence was reported to lead to a strong salty taste in the mouth. This phenomenon is easy to explain: the Island of Reil involved in the sense of touch receives a strong gustatory signal from the tongue and sometimes integrates taste and perception of roughness [66].

In some people with time-color synesthesia, days of the week or months are associated with specific colors, e.g., Monday with green, Wednesday with pink, December with yellow. In such people, the abstract notion of a numerical sequence rather than a digit image evokes a sense of color. In this case, brain anatomy matters a great deal. After the digit image is recognized, information is sent to angular gyri the brain area in the parietal lobe most responsible for the treatment of color-related information at the highest hierarchical levels [66].

A collection of receptors manipulates the signs of an observed object by breaking them into various modalities. The bits of information about these signs go to the brain regions that integrate them into a whole and keep memory of the analysis and synthesis procedures. These procedures were described in terms of the integration of essential traits by M M Bongard (1924–1971) in his interesting book, *Problems of recognition* [107]. Bongard was affiliated with the aforementioned Laboratory of Vision Biophysics. He used in his studies approaches developed by the senior generation of Lazarev's co-workers.

6.3 On the relationship between visual reception and motor function

P P Lazarev wrote in 1918: "the study of this phenomenon [13] can reveal important aspects of creative work and imagination" [51]. In 2018, the state TV channel Rossiya-1 launched the 'Udivitel'nye lyudi' (Amazing People) project, a competition giving participants the opportunity to demonstrate the unique abilities of their brains developed by mnemonic techniques.

The history of humankind is inseparable from the development of memory. The oldest mnemonic texts that have come down to us appeared in ancient Greece, as exemplified by the legend of the 'memory theater' by the ancient Greek poet Simonides (5th century BC) [107]. Evidently, the art of memory was especially important in the preliterate period. The ability to keep in memory not only individual experience but also that of predecessors, together with the ability to transfer it to the next generations, was highly esteemed as a mode of a community's adaptation to an aggressive environment. Priests, shamans, and storytellers had to remember large amounts of information and transfer it by word of mouth to their tribespeople. The art of memory remained equally important after the advent of written language. The high cost of papyrus and the large size and weight of early books motivated people to look for ways to remember large volumes of information. Nomadic tribes and caravans of merchants covering large distances had to reduce the weight of the load and rely on memory. Medieval monks also did their best to cultivate the art of memory to be able to participate in disputes concerning interpretations of various 'sacred texts'.

[13] Lazarev means mnemonics, i.e., the totality of means for facilitating remembering useful information by the formation of associations and substitution of abstract objects and facts by notions and views having visual, auditory, and kinesthetic representations, allowing new objects to be related to those already stored in memory.

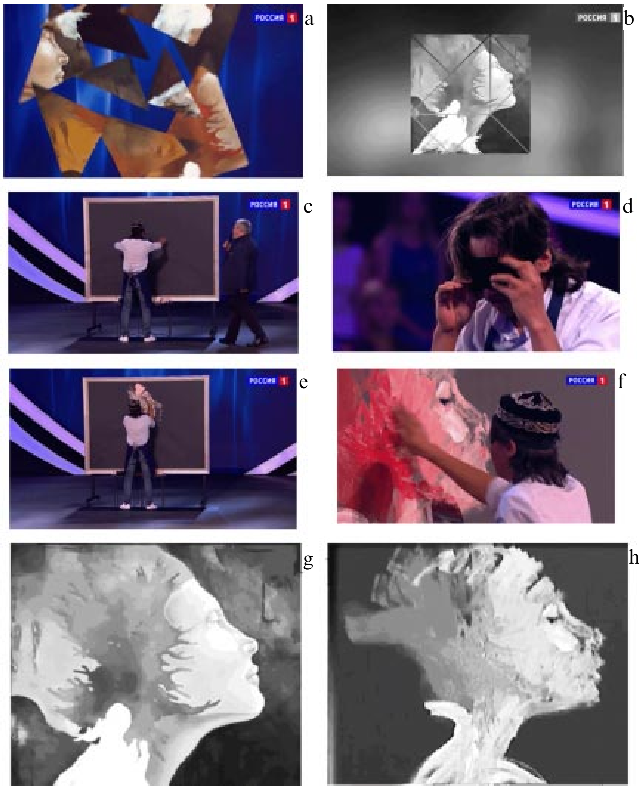

Figure 6. Relationship between the visual system and motor skills (see the text). The lower pair of slides show the real picture (g) that the artist could see only in the form of moving parts (h) and the picture he drew when put blindfolded in front of a canvas.

Turning back to the show 'Udivitel'nye lyudi', it should be mentioned that the jury panel time after time expressed great surprise at seeing manifestations of unusual forms of memory based on the combination of different receptor systems. By way of example, Renat Elubaev, an artist from Kazakhstan, managed to demonstrate unique brain properties within the visual reception → motor memory → hand movements paradigm. He was asked to look for two minutes at parts of an image of a woman's face (Fig. 6b) he had never seen before, which were rapidly moved on the screen in a random fashion (Fig. 6a). Then, he was put blindfolded in front of a canvas (Figs 6c–e) and asked to recreate in five minutes the whole picture that he was expected to form in his imagination (Fig. 6f). The result proved interesting. Curiously enough, the artist moved both hands as he watched the parts moving. In other words, he relied on motor function to reconstruct the whole image.

7. What is synesthesia: the genetic echo of the past or an acquired but noninheritable property of adaptation to environmental variations?

How synesthesia originates and develops is unclear. At least three hypotheses have been proposed to explain this phenomenon.

The first is the so-called semantic vacuum hypothesis, according to which synesthesia develops in childhood when children begin to familiarize themselves with abstract phenomena. The primary abstract notions (e.g., letters) that children learn to recognize using color pictures contribute to the coupling of color with the respective notion (red letter M and the picture of a melon nearby, yellow letter B and the picture of a banana, etc.). Such manner of teaching children genetically predisposed to excitability promotes the formation of strong associations between letters and colors. This hypothesis explains why grapheme-color and digit-color synesthesias are the most widespread forms of this condition [90]. However, it does not account for its other forms, related, for example, to taste and motor function.

Second, there is the so-called semantic hypothesis [108]. Its main disadvantage is that it tries to explain one phenomenon (synesthesia) in terms of another that has been poorly explored (the search for meaning).

The third (adaptive) hypothesis tends to reconcile the former two. It was shown in one of our studies [83] that the organism (a self-organizing far-from-equilibrium system) looks, in response to a change in the environment, for a new way to retain stability and thereby to survive under conditions of uncertainty. Stress and emotions can provoke synesthesia to facilitate the search for stability. Moreover, synesthesia is likely to arise in connection with prolonged intense creative activity, meditation, or drug consumption (cannabis, LSD) [109].

There is reason to believe that synesthesia is an invariable attribute of human communities. Synesthetes could somehow have contributed to the survival of humankind in its early ages when the human population density was very low. The brains of synesthetes acquired the ability to associate colors with sounds and smells, which they used to recognize beasts of prey hiding in thick vegetation. Also, members of different tribes had to exercise prudence and care when they met to avoid being cannibalized during food shortages. Some modern chimpanzees and baboons are inclined to turn to cannibalism [110]. These facts explain why P P Lazarev's interest in the problem of camouflage laid special emphasis on the study of the close interrelationships among different sensory systems.

Assuming that progress and the advancement of civilization were accompanied by a shift of competition in human society into the sphere of mental work and creative activity, it is easy to understand why the number of synesthetes is growing. The increasingly complicated associative thinking based on the enumeration of connections between neuronal clusters in the continuously working brain of a writer, artist, composer, researcher, or engineer leads, in the absence of adequate inhibition, to their merging.

This allows us to consider *synesthesia, on the one hand, as the genetic echo of the past; on the other hand, it is an adaptive but noninheritable property acquired recently as a consequence of continuous mental work*.

8. Discussion of mechanisms of synesthesia

8.1 Role of memory in information compression

Memory forms the basis of the *virtual world in our brain*. It is the accumulated genetic experience inherited from the parents and selected in the course of evolution of the species Homo sapiens, together with the experience acquired during the life of a human person either from other people or through one's individual effort by trial and error. The virtual world should be described on the assumption of Einstein's theory of relativity and the quantum mechanics of Schrödinger as boundary conditions from above and from below, respectively [83].

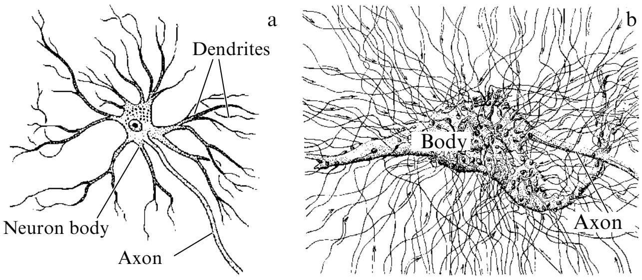

Figure 7. Neuron: (a) simplified diagram, (b) numerous synapses on its body.

There is a popular belief that time is the sole measure of memory [111]. This assertion is incomplete, because it implies that an organism's own time does not differ from external astronomical time.

In the framework of the relativity theory, it is possible to speak about an 'instant of time' only with regard to a specified reference frame. Time shown by a clock moving together with a given object is actually its proper time. Memory records an event at a certain external time point t and thereby prevents it from changing inside the brain. This permits us to repeatedly recall the event.

Memory can manipulate stored events in a variety of ways, e.g., turning time back like rolling a film backward. Moreover, it can extract fragments of events and perform logical and combinatorial operations with them to design a set of scenarios to be stored in the memory. In a word, time in the virtual world of our brain is a variable and reversible entity, unlike that in the real world.

A newborn baby is capable of breathing, swallowing, falling asleep, and awaking. It grows, starts to recognize members of the family, and adapts its circadian cycle to environmental cues: it is awake in the daytime and sleeps at night. Its brain improves the ability to find similarities and differences between objects and events. The model of the virtual world in its brain expands, and numerous associations are formed between past events. The brain of an adult person contains some 86 billion neurons and 100 trillion synapses between them (Fig. 7) [112].

Hence, the average number of synaptic connections per neuron is $\sim 10^3$. If each link is a binary code (1 — connection, 0 — no connection), each neuron can remember in the limit the amount of information I:

$$I = \log_2 10^3 \text{ bits.} \tag{11}$$

The overall volume of memory supported by the totality of brain neurons is on the order of

$$I_\Sigma = 86 \times 10^6 \log_2 10^3 \approx 86 \times 10^7 \text{ bits.} \tag{12}$$

Human memory seems to be extraordinarily capacious, but it is actually far from being such compared with modern computers.[14] The most important advantage of the human brain is not the large volume of memory but the possibility of its multistep compression and rearrangement, as well as the ability to forget irrelevant information. Memory retaining all useless information would be immediately overfilled and unable to interact with the environment.

[14] 1 GB = 2^{30} bytes, 1 byte = 8 bits.

The first step of information compression occurs at the input of the information processing system. Environmental parameters of importance are the onset time, rhythm, periodicity, and repetition rate of events. An organism perceives some events as discrete, either happening one after another in a series or merging together to be perceived as a unified whole. Humans perceive two flashes of light less than 50 ms apart as a single one. Temporal resolution abilities of living organisms were adjusted during evolution to the reactions of their locomotor apparatus. The 'impact-response' interval was divided into two parts. Of course, it makes no sense to differentiate between events (all the more so to transfer them into memory) if they can not be responded to. In this context, humans are not an exception in the animal world. The only difference is that they invented external long-term memory, which enables us to preserve accumulated information beyond life's limits of an individual and transfer it to the descendants. This is what we call culture and social interaction, including verbal communication, petroglyphic drawing, written language, architecture, typography, text-books, encyclopedias, reference books, and, finally, the Internet).

Let us turn back to information processing. To begin with, the virtual model of the external medium forms in the nervous system as a result of neuron-to-neuron interaction, but we know the language of neurons only at the level of potentials they produce in response to electric stimulation under experimental conditions (Fig. 8b). Such an impact does not lead to a dialog with a neuron; it induces no more than its 'call for help'. Second, the problem is not only and not so much how to ensure the optimal conditions for filling the memory volume but how to find in this volume the stored solution to a given problem for its reutilization.

Moreover, the virtual model of the external world formed by the neuronal network is dualistic, being both material and nonmaterial. It is supposed that material and nonmaterial worlds are related through information-entropy transitions [113, 114]. The Carno cycle demonstrates this relationship at the macrolevel, which is frequently referred to as the negentropy principle of information. The final result of such an approach is relatively simple: the cost of extraction of any information from the memory is equivalent to or higher than the increase in entropy in the entire system [115]. However, the use of entropy to characterize the work of a living system (especially the brain) proves insufficient for the purpose; it neither allows a comprehensive description of its principles nor provides deep insight into its underlying mechanisms [116].

Let us consider four stages in the biophysical description of information processes in the brain, including extraction of necessary data from the memory:

1. The brain interacting with the environment operates at the borderline between order and chaos [117, 118]. The information processing rate is measured in conventional units (bits, bytes, etc.) referring to the time of information transfer in space [119], taking into consideration the value of the extracted information that depends on the goal either dictated by the external conditions or set by someone guided by an inward impulse or motivation for the improvement of the stability of a living organism, i.e., its adaptation to environmental variations. The brain remembers successful variants of adaptation. Target setting implies the choice of an optimal strategy for the achievement of the goal [117]. Such a view of the reasoning mechanism allows the value of information to be described in terms of increased probability of reaching the goal [106].

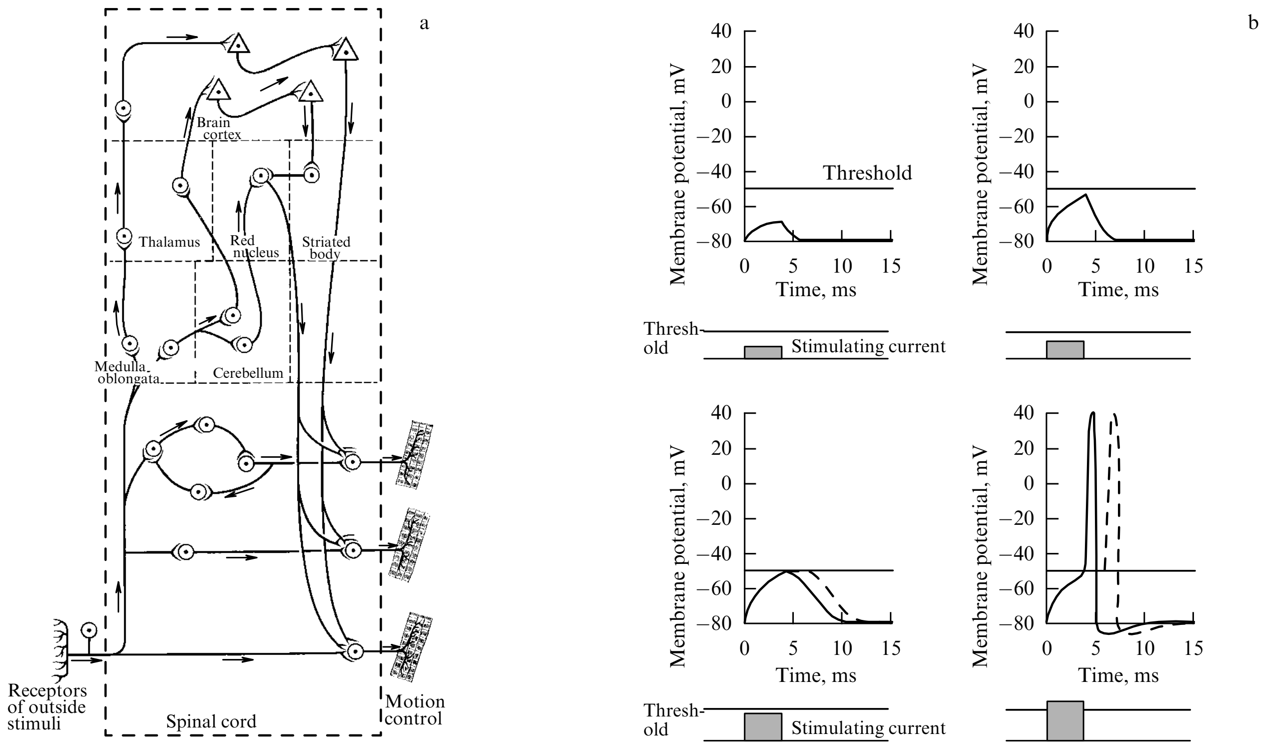

Figure 8. Simplified schematic of the levels and links in the nervous system (a) and a neuron's electrical responses (b) revealed by measuring membrane potential during axon irritation by electric currents of different strengths (sub- and suprathreshold [112]).

2. The path to achieving the goal depends on the external situation and a priori information contained in memory. If the problem reduces to obtaining an integrative view of the observed outside world by the assembly of a set of n fragments, the virtual model implies the transition from chaos, i.e., complete enumeration of n fragments, to order. In other words, a determined model is constructed based on stepwise compression of information that enhances its value. It must yield an instruction for transitions along the chaos-to-order chain: $\{(n!) \approx n^n\} \to \{n(n-1)/2\} \to \{n-1\}$. Suppose that a whole image consists of only 10 fragments and assume that a single operation of assembly of the whole from fragments takes only 6 seconds. Then, the assembly in the absence of a priori information remembered earlier needs 6 s $\times n!$ to be completed, i.e., 2×10^3 years of continuous search for a solution; systematized block enumeration with an additional information criterion requires 4.5 min; less than 1 min is needed for assembly in accordance with the formulated and remembered instruction. It is a clear illustration of the cost of the previously remembered information about relationships between events [120]. Information compression can be arbitrarily broken down into any number of stages; two stages can be distinguished in the limit: (1) memorizing current information and (2) identifying valuable information by increasing the neuron excitation threshold to cut off the ones that are not valuable (Fig. 9).

3. The levels of organization of information processing can be presented in the form of a matrix of vertical columns along which information flows move from receptors to the brain cortex and nodes where it is processed [121]. Figure 10 presents a schematic illustration of the increase in the number of information-analyzing levels during evolution, from protozoans to humans.

The matrix of the number of levels in the columns analyzing information grows from microscopic to more complicated organisms. Even in higher insects and vertebrates, from fish to birds, the analyzing system has at least four levels of information processing. Mammals have the fifth level, the brain cortex. Accordingly, the number of horizontal connections between clusters and the volume of memory increase. The number of neurons at different levels of visual and hearing information processing in monkeys and humans was determined in the mid-20th century [122, 123]. The number of neurons at level I (inner ear) of the analyzing hearing system of a monkey was found to be $\sim 3 \times 10^4$, at level II (medulla oblongata) $\sim 9 \times 10^4$, at level III (midbrain) $\sim 4 \times 10^5$, at level IV (diencephalon) $\sim 4 \times 10^5$, and at level V (auditory cortex) $\sim 10^7$. Obviously, the step of transition from one level to another varies in terms of the number of neuron clusters involved. The upward transition is far from smooth, i.e., the ratios of the number of neurons at the ith level to that at the $(i-1)$th one are: 3, 4, 44, 1, and 25, respectively.

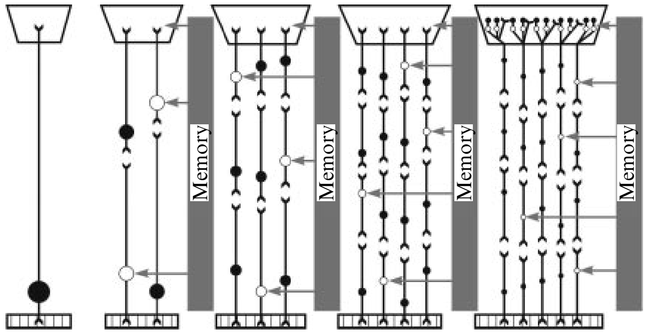

Figure 10. Schematic of evolutionary rise in the number of levels analyzing information in animal biosystems. Left to right: from protozoans to humans. Vertical hatching below denotes the receptor surface in contact with the outside medium. The black dot with bars indicates a neuronal cluster (hub); the quadrangular surface at the top stands for the brain cortex. An increased number of parallel chains conventionally depicts the rise in the total number of levels involved in information treatment and transfer from a receptor to the brain. The schematic on the right corresponds to that in Fig. 7.

The appearance of new levels sometimes occurs in accordance with the fractal principle of similarity. In this case, their description encounters no difficulty due to the repetitive occurrence of operations owing to the similarity of information movement from low to high levels [55, p. 157]. These so-called L-systems of A Lindenmayer were investigated back in the 1970s [124, 125]. However, such systems are rather the exception than the rule.

The treatment of information in the brain resembles the process of its changes at the quantum level, where fixation of photons interacting with their detector is described in terms of wave function collapses [126, 127]. Hence, the conclusion appears that remembering signs of one element of the system alters information interaction between the rest signs. In the limit, remembering a random choice converts its probability to 1, while the remaining probabilities vanish [128, 129].

4. The hierarchical multilevel nature of memory and its treatment, as well as that of estimating the value of informational signs in living organisms, preclude a comprehensive analytical description of the work, even at a single level. The problem is that the language of the description must be analogous to the language of communication between system elements (neuron cells occupying this level). However, we do not know this language-conf Smoluchowski [129] that a researcher studying the treatment of information in the brain is akin to a military commander: *he can not perceive the identity of neurons for the lack of means to identify it*; *by no stretch of the imagination can he do any more than determine the number of identical neurons whose positions and processing speeds remain confined within some limits. However, these parameters are insufficient to understand the processes at each information level, because the meaning of the 'talks' between the neurons does not yet make sense to us.*

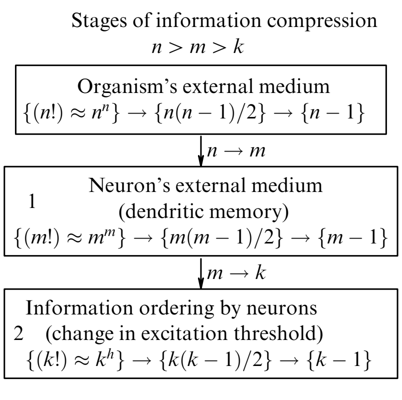

Figure 9. Information packaging in the virtual model memory inside the brain has a hierarchical structure. The scheme demonstrates stages of information compression during memorizing and generalizing the signs of the external medium in the internal one.

8.2 Information processing in networks

Depending on the surprises delivered by external medium, the brain has to solve the problems arising in the environment under conditions of time t and/or energy W shortage. It must comply with the action cost limit $H = Wt$. Let us show that synesthesia is an evolutionary tool for reducing barriers that hinder overcoming these deficiencies, especially that of time. It occurs whenever the problem needs to be solved for characteristic time τ satisfying the condition $\tau \leqslant \Delta t_{\text{cr}}$, where Δt_{cr} is the critical time interval. The consequences of the failure to meet this condition differ. The cost to be paid is especially high in predator $\leftrightarrow$ prey systems. Overranging Δt_{cr} leads to the death of the predator by starvation or the prey falling victim to the predator. In other situations, the cost reduces to the temporal loss of stability that tends to recover with time [83].

Here is a simple example demonstrating the influence of the number of information levels on the solution to problems related to image recognition under conditions with mutual influence of the amount of information being treated and that of the previously remembered one. Figure 11 demonstrates such a situation as exemplified by a neuron network in the form of a graph. The shortest route from point A to point B needs to be found during minimal time.

In each node formed by neurons of different hierarchical levels, the treatment of information at each transition step takes time τ_{ij}. The total time needed to process information τ_{Σ} between points A and B in the case of equal steps $\tau_{ij} = \tau_{(i+j)}$ is

$$\tau_{\Sigma j} = n\tau_{ij}\,, \tag{13}$$

where n is the number of steps between hubs along the jth path. If $\tau_{ij} \neq \tau_{(i+j)}$, expression (13) assumes the form

$$\tau_{\Sigma j} = \sum_{i=1}^{n} \tau_{ij}\,. \tag{14}$$

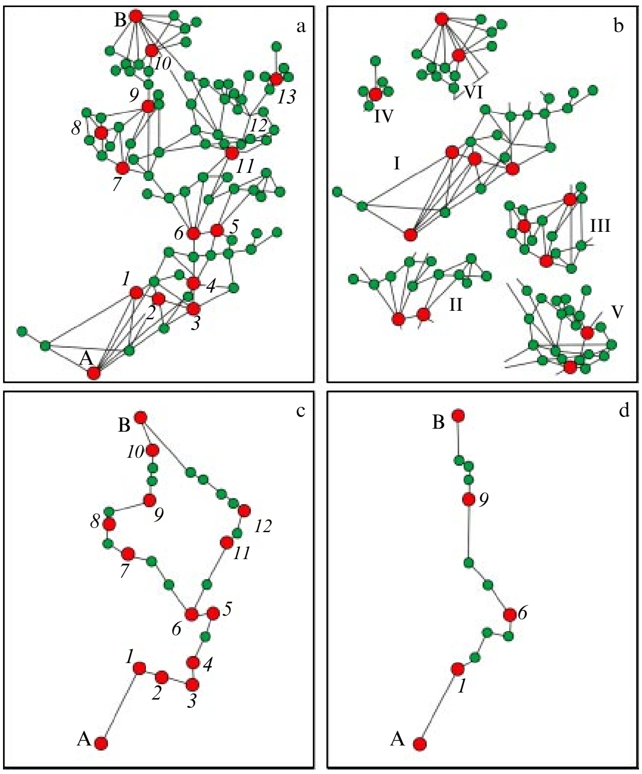

Figure 11. Hypothetical neuronal network (a). Dark (red) dots indicate 15 hubs for which connections are distributed within the range $\deg(v) = 5-7$. It is well apparent that the network can break down into 5 or more clusters as soon as information is forgotten, i.e., as connections die out (b). Suppose that an information flow must be displaced from point A to point B, with only the direction but not the pathway of transfer being known. The shortest path needs to be found. Figures (c) and (d) show two variants of the problem solution by the trial-and-error method.

The left path in Fig. 11c consists of 11 steps, with 6 steps to bifurcation No. 6. The right path consists of 9 steps. In other words, it is $(11-6)/(9-6) = 5/3 = 1.67$ times more advantageous than the left path in terms of time consumption. However, there is one more path from A to B (Fig. 11d) consisting of only 4 steps. If found, it is $11/4 = 2.75$ and $9/4 = 2.25$ times more advantageous in comparison to the left and right paths in Fig. 11c, respectively.

The transmission time along neuronal pathways is rather short due to the high impulse speed in axons (30 m s^{-1}). This means that an information flow covers a distance of 3 cm in 1 ms. Most delays are caused by the treatment of information in the hubs with a large number of connections (synapses). If a hub has roughly 10^3 synaptic contacts of equal weight and it is necessary to choose during the learning process one of the many paths determining the direction of further movement, the probability of randomly guessing correctly the optimal path is very low, $p = 0.001$. However, the search time can be shortened. Biological systems have found an advantageous strategy known as trichotomy or ternary search. Synapses are not uniformly distributed over the neuron body, because a frequently repeated optimal solution path is characterized by higher synapse density. Synapse density is low in association with rarely solved problems and reduces to a minimum in the solution to new problems. It is a priori unclear from the condition of a problem whether it is new or was solved many times before. Therefore, a maximum synapse distribution density needs to be found for multiply addressed problems and a minimum location function for new problems. The ternary search is based on the fact that both maximum and minimum synapse densities (functions of memory) lie between the first and last thirds of their spatial distribution. The ternary search demonstrates the following paradigm: avoid extremes and look for a compromise. In biology, such a principle is called symbiosis. Suppose that an excitation signal that reaches a neuron has to look for an optimal way to solve a totally new problem. It needs the minimal synapse density function $f(x)$ that lies between ρ_1 and ρ_2. For the algorithm to be applicable, there must be a certain x value satisfying the following condition:

- for all a, b for which $\rho_1 \geqslant a > b \geqslant x$, $f(a) > f(b)$ is fulfilled;
- for all a, b for which $x \geqslant a > b \geqslant \rho_2$, $f(a) < f(b)$ is fulfilled.

In fact, this manner of search for the optimal way is a variant of the 'method of ravines' proposed by I M Gel'fand and M L Tsetlin in the early 1960s [130, 131]. Software versions of such methods are described in [132].

Finally, how does synesthesia come into being? Turning back to Fig. 11b, one can easily see that the path between point A (goal setting) and point B (finding a solution) in the graph passes through different hub clusters (neuron associations). Some of them are centers of vision representation in all its multiplicity, including color and visual images, others are hearing representation centers, taste representation centers, etc. Passage along these graph trajectories can lead to the merging of a path stored in the network with different colors imposed by representation centers of other receptor systems and thereby create a new world of images in the problems being solved. This influence transferred through the growth of synaptic systems produces new signs in the problems. These signs are remembered which excludes uncertainty in the choice of the pathway during a repeated search.

In a word, reproduction of memory traces implies symbiosis, i.e., positive interaction with a rise in the number of synaptic connections. The appearance of synesthesia is a consequence of symbiosis between memory elements, which can result in the limit in their complete fusion.

8.3 Synesthesia eliminates perception uncertainties

Here is a simple example. Consider the following problem: *it is necessary to assemble one square and one rectangle without multivaluedness of the solution from a double set of two groups, each containing 6 identical pieces. All the pieces must be used for the purpose* (Fig. 12). The complete random enumeration of the six pieces from each group $6! = 720$. The total area of all pieces in each figure being the same, the areas of the assembled figures are equal (Fig. 12a).

An adult person having no previous experience needs 2–4 min to assemble the grey pieces. Interestingly, such persons usually do not realize which signs they use to assemble the figures. The typical answer is: "This pieces is suitable and that one is not." Moreover, in most cases, the assembler fails to notice the uncertainty that arises during assembly of the rectangle as a result of rearrangement of three squares; in other words, there are six variants of this assembly. The number of permutations of the squares inside the rectangle $P_3 = 3! = 6$ (Fig. 12b).

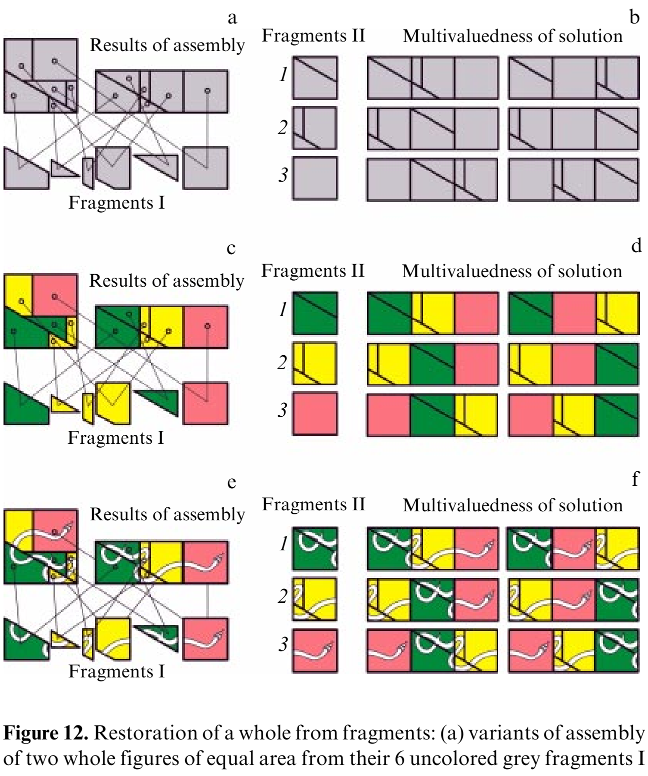

Figure 12. Restoration of a whole from fragments: (a) variants of assembly of two whole figures of equal area from their 6 uncolored grey fragments I of the first level, (b) ambiguity of the solution in the presence of uncolored grey fragments II of a higher rank, (c) variant of assembly of two whole figures of equal area from their 6 colored fragments I of the first level, (d) multivaluedness of solution in the case of assembly from a set of colored fragments II of a higher rank, (e) assembly of two whole figures of equal area from their 6 colored fragments I of the first level with the superimposed variant of the snake image (fragments III of the third level), (f) multivaluedness of solution is eliminated by the use of an additional essential sign (snake image), because it is preserved in a single variant of assembly but breaks up in all others.

Let us introduce an additional sign (color) for pieces I of the first level (Fig. 12c). This permits assembling a whole from pieces II in the form of squares of different colors. In this case, the assembly is the subset not only of geometric figures but also of the set of color variants readily distinguished by the human eye (Fig. 12d). Certainly, this set is different for a color-blind person. Six solutions for the assembly of the rectangle immediately offer themselves.

The probability of the choice of any of them is $p_i = 1/6$. However, the problem formulation contains the unavoidable condition 'without multivaluedness of the solution'. Therefore, the random choice of any of the six variants falls in line with the problem solution. But, what variant should be chosen? Let us think, say, of the sixth one corresponding to a usual set of traffic lights; in this case, $p_6 = 1$, and the energy of color photons increases from right to left, i.e., from red to green. In such a choice, all other probabilities of assembly are zeroed because memorizing a random choice eliminates alternatives [128]. But, how can such choice be substantiated?

Let us introduce one more additional sign (Figs 12e, f). The superposition of a meaningful image, e.g., that of a snake, on the assembled figures (colored square and rectangle, respectively) eliminates the uncertainty, and the image of the object in the memory of the assembler becomes the main information sign, while the role of the remaining signs (geometric shape and color of the pieces) diminishes. The uncertainty in the assembly of the rectangle disappears. Only one combination of pieces II gives the whole snake image; this means that $p_1 = 1$, while all the remaining $p_i = 0$.

Thus, our brain is not only an interface correlating genetically-determined programs (instincts) and their realization under environmental conditions [56], but also an adjudicator handling in its virtual model inner competitive situations between sensations and eliminating uncertainties by sign separation and combination.

To sum up, synesthesia is a form of cognition of the surrounding world facilitating the perception of environmental signs of different hierarchical statuses (Fig. 1). This process makes it easier to a priori evaluate received information and thereby increases the probability of a problem solution due to the elimination of uncertainties.

9. Conclusion

1. In the early 20th century, P P Lazarev postulated the possibility of a union between sensory impressions in humans. Lazarev's interest in the global problems of the modern world was ahead of his time.

2. Lazarev founded several scientific schools. His treatment of seemingly special applied problems was always based on a systemic approach with the involvement of various specialists. Unfortunately, the political leadership of this country busy with the problem of its own survival, could not at that time appreciate in full measure his talent. On the contrary, they sowed the seeds of discord and favored the malicious smear campaign against the outstanding scientist.

3. Synesthesia is not a pathological condition but a normal physiological process, even if it does not occur in most people. The mechanism behind the appearance of synesthesia is a manifestation of a symbiotic relationship between various elements of memory, reducing the storage time of approaches to solving the problem for their reutilization in the future.

4. Synesthesia is, on the one hand, the genetic echo of the past and, on the other hand, an adaptive noninheritable property acquired recently in the course of continuous mental activity.

5. Many creative people experience conditions suggesting the interaction between different receptor systems during intense mental work and, as a result, a combination of receptor perceptions.

6. At present, interest in the study of this phenomenon has spread not only in the neurosciences but also in many areas of social and physico-mathematical sciences in connection with the creation of artificial intelligence systems and creative android robots.

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