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# Auditory, visual and proprioceptive integration as a substrate of language development

*Integración auditiva, visual y propioceptiva como sustrato del desarrollo del lenguaje*

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## | Abstract |

**Introduction:** Language development is a complex process that may be considered as an evolutionay trait in human beings; it is possible to undetstand said process by evaluating the contribution of sensory systems and the events that frame critical periods of development.

**Objective:** To conduct a literature on how auditory, visual and proprioceptive information integration occurs in language development, as well as the role of social interaction in this process.

**Materals and methods:** The MeSH terms "Language Development"; "Visual Perception"; "Hearing"; and "Proprioception" were used, limiting the main search to articles written in English, Spanish and Portuguese. The databases consulted were Medline and EMBASE.

**Results:** Auditory information is the first sensory stimulus to consider because, during the first year of life, the infant recognizes and discriminates environmental signals that correspond to language, followed by a peak in its acquisition and, subsequently, by a stage of maximum linguistic discrimination. Visual information allows correlating language with images since it acts as the substrate for the designation and understanding of words, as well as for interpretation and imitation of the emotional component in gesticulation. Proprioceptive information provides feedback on motor performance patterns used in language production.

**Conclusion:** This perspective offers new points of view for treating and managing deviations in language development.

**Keywords:** Language Development; Sensory Functions; Sensory Deprivation; Visual Perception; Hearing; Proprioception (MeSH).

## | Resumen |

**Introducción.** El desarrollo del lenguaje es un proceso complejo considerado como marcador evolutivo del ser humano y puede ser comprendido a partir de la contribución de los sistemas sensoriales y de los eventos que ocurren en periodos críticos del desarrollo.

**Objetivo.** Realizar una revisión de cómo se da la integración de la información auditiva, visual y propioceptiva y cómo se refleja en el desarrollo del lenguaje, destacando el papel de la interacción social como contexto que favorece este proceso.

**Materiales y métodos.** Se utilizaron los términos MeSH "Language Development"; "Visual Perception"; "Hearing"; y "Proprioception en las bases de datos MEDLINE y Embase, limitando la búsqueda principal a artículos escritos en inglés, español y portugués.

**Resultados.** El punto de partida lo constituye la información auditiva, la cual, en el primer año de vida, permite la discriminación de los elementos del ambiente que corresponden al lenguaje; luego un pico en su adquisición y posteriormente una etapa de máxima discriminación lingüística. La información visual proporciona la correspondencia del lenguaje en imágenes, sustrato de nominación y comprensión de palabras, además de la interpretación e imitación del componente emocional en la gesticulación. La información propioceptiva ofrece la retroalimentación de los patrones de ejecución motora empleados en la producción del lenguaje.

**Conclusión.** El estudio del desarrollo lenguaje desde la integración sensorial ofrece nuevas perspectivas para el abordaje e intervención de sus desviaciones.

**Palabras clave:** Desarrollo del lenguaje; Modalidades sensoriales; Privación sensorial; Audición; Percepción visual; Propiocepción (DeCS).

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## Introducción

Language development is an evolutionary marker in humans, frequently taken as an object of study by different disciplines. (1) A large number of questions have been directed to study how the infant detects stimulus from the environment through audition and visual means, which is essential for language acquisition, conveying meaning and acting as the necessary input for interacting with the environment. (2-4) This perception, along with the proprioceptive information generated by the motor activity of the phono-articulatory system, stimulates auditory-visual-motor integration, which is a fundamental element for comprehensive and expressive language development. (3,5,6) This is evident in children with sensory deprivation (deafness or blindness) and other conditions like Autism Spectrum Disorder or immaturity caused by preterm birth, in which inadequate processing and integration of sensory input are observed. (3,7-9)

The contribution of each sensory system to language development can be understood from the theory of sensory integration, which offers a framework for assessment and intervention in neurodevelopment. This theory, developed by Jean Ayres, occupational therapist, suggests that sensory information is integrated and processed in the central nervous system, where each stimulus can be perceived, categorized and assigned an emotional quality. These perceptions and emotional qualities guide the response to the stimulus. (10) Thus, neurodevelopment at each stage is the result of the ability of an individual to integrate the received sensory information and processing it effectively. (11)

Although, language itself is considered an integration level prior to higher thought processes, the foundations of its development are based on the basic levels shown in Figure 1. (11,12) Auditory/vestibular information is the starting point that allows detecting the source of sound, differentiating that which is inherent to language, and starting with the process of familiarization with the features of the mother tongue. (3,5,13) On the other hand, visual information allows obtaining gestural correspondence with what is heard, and associating the perceived objects with the sound that refers to them. In this way, the meaning of language and the basis for imitation of both gestures and phonation patterns are structured. (5,6,14,15) Proprioception from facial, oropharyngeal and laryngeal muscles provides the third form of feedback of phonation processes in language production, key element in the development of expressive language. (16-20)

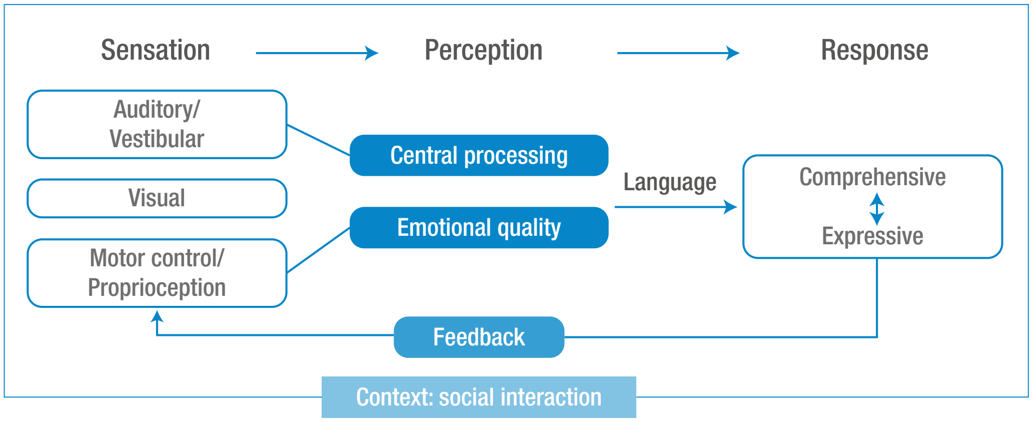


**Figure 1.** Sensory integration, a substrate of language development.
Source: Own elaboration.

The objectives of this review are, first, to describe how auditory, visual and proprioceptive information integration in language development occurs and, second, to highlight the importance of the contribution of each system based on sensory deprivation and dyspraxia. Additionally, this work intends to suggest sensory integration as a tool for approaching deviations in language development. This review is specially directed to medical students, residents and pediatricians who work with infants and children in a clinical context.

## Methods

The main search was conducted in the Medline and EMBASE databases using the Medical Subject Headings (MeSH) terms "Language Development", "Visual Perception", "Hearing", "Proprioception", and derived terms. Subsequently, a filter by language was added, selecting English, Spanish and Portuguese. Only articles published between 2000 and 2016 were included. For this narrative review, the relevance of the titles and abstracts was analyzed according to the objectives, and then, the selected articles were included. Some reference books related to the topics addressed were also analyzed. The search strategy is shown in the PRISMA flow diagram of Figure 2.

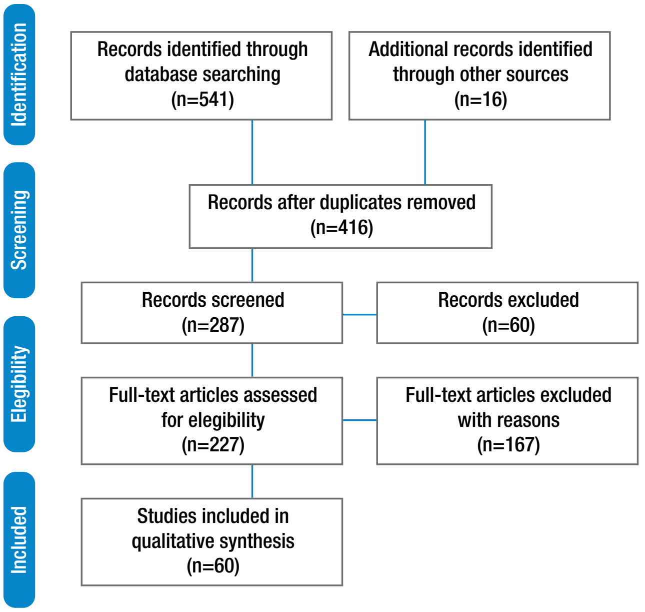


**Figure 2.** Search strategy.
Source: Own elaboration.

## Results and discussion

### Auditory information: the starting point

The study of the relation between the auditory system and language has been conducted since the intrauterine stage, characterizing the critical period for auditory development as the key milestone of language development. (21,22) As shown in Table 1, this period comprises the beginning of the third trimester of gestation until the twelfth year of life, moment when anatomical and functional circuits in development are likely to be modified by external elements. (3,21,22) In consequence, the experience of the individual becomes a determining factor in this process, so exposure to appropriate stimuli will have a positive impact on development, while deprivation will have a negative effect. (23-25) Moreover, exposure to and familiarization with the mother tongue, since the early stages of the first year of life, facilitates the specialization of phoneme recognition, going from a universal to a particular capacity. (2,16)

**Table 1.** Auditory system maturation and its effects on language development.

| Age | Anatomical and functional structure related | Effect on language development |
|---|---|---|
| Early third trimester of pregnancy | Cochlea is similar to adult cochlea | First behavioral responses to sound (peristalsis, heartbeat, maternal voice, external noise) |
| | Olivocochlear circuit maturation | |
| | Descending control from inferior colliculus | |
| 1st year | Auditory pathway myelination from brainstem to auditory cortex | Detecting sounds, differentiating that which is inherent to language. |
| | | Familiarization with mother tongue phonemes |
| | | Assignment of first meanings to words |
| 1-5 years of age | Increase in dendritic arborization | Language acquisition period |
| | Axonal maturation in the deep layers of the auditory cortex | |
| 5-12 years of age | Axonal maturation in the superficial layers of the auditory cortex | Peak linguistic discrimination |
| | Connection with adjacent association areas | |

Source: Own elaboration based on (3,21,23).

Anatomical and functional changes have been identified as the result of sensory deprivation in the critical period of auditory development. (3,23,26) If deprivation occurs during the perinatal period, the stream from the cochlea to the brainstem becomes affected, showing, from a histological perspective, lower dendritic arborization and defects in the axonal and synaptic organization. Consequences are also seen in the incipient cortical organization, downregulating the expression of dendrites of the boundary layer.

Sound deprivation during childhood is demonstrated by the delay/absence of cortical myelination and, thus, a defect of synaptic maturation. (3) From a functional perspective, deprivation in the perinatal period may affect acoustic discrimination and attention to sound stimuli, altering the designation process; if it occurs during childhood, deprivation generates defects in auditory processing, as well as difficulties in understanding the meaning of words, acquiring vocabulary and discriminating sound. (3,26) Bearing this in mind, anticipatory strategies for timely detection of hearing loss are being developed for early intervention to lessen the effects of sound deprivation, especially in individuals at high auditory risk. (23,27,28)

Researches have taken auditory information and the effects of sound deprivation as the starting point of sensory integration, necessary for the development of language. They also attempt to demonstrate how timely access to amplification devices or cochlear implants favors this process. Most studies, which have been carried out since the 1990's, seek to measure the impact of cochlear implants and to establish the appropriate moment for implantation. (12,29,30) More recently, the Childhood Development and Cochlear Implantation (CdaCI) study has published at least twelve works since the creation of the cohort in 2007, thus becoming a benchmark in this topic.

One of these publications, done five years after the procedure, showed that implanted children not only had a significant improvement in comprehensive and expressive language, compared to the measurements collected before the implant, but also that it was possible to establish the importance of this procedure at an early age. In patients implanted after the age of three, the improvement of these skills was lower. (31) Similarly, these results have been replicated in other areas of language development, mainly those related to attention, communication skills and general behavior. (32-34)

### Visual information: connection between language and images

Most information of the outside world gathered by humans is provided by the visual system, which is a key element for planning and motor control processes, learning and constructing language. (2,35-37) Similarly to the auditory system, the general anatomical references of the visual stream are developed at birth, but their functional maturation occurs during the postnatal period, with a critical period that comprises birth until age five. (38) The greatest evidence is found in the first year of life, when the visual system activity is regulated by the superior colliculus, which reflexively determines orientation to objects.

Between two and four months of age, when cortical-quadrigeminal circuits and binocular vision develop and visual acuity improves, the infant is able to perform voluntary fixation, explore the environment and begin to take interest in and hold the objects around. During this period, the action of the dorsal visual stream (occipital-parietal association area), responsible for the kinematic parameters of vision, prevails. (35,36,39)

At six months, the infant develops photopic vision; the cones reach maturity and concentrate in the fovea, which makes possible not only color vision but the recognition of the characteristics and functions of the object, corresponding to the ventral visual stream (occipital-temporal area association). Finally, at around eight months and with the arrival of afferents from the premotor cortex to the superior colliculus, full control of eye movements and coordination between them and cervical movements are achieved. (40) These processes are benchmarks of visual attention development in the first year of life, and represent a level of integration that allows the development of individual visuospatial skills. (36,38,40) Conditions such as prematurity may cause deviations in the acquisition and development of these skills. (41)

A sample of the important contribution of visual information to sensory and language processing is found in the work of Guerreiro *et al.* (42), who used a functional magnetic resonance image (fMRI) to compare the response to visual and auditory stimuli in a group of individuals with congenital cataracts against a group of individuals with normal visual development. The individuals were subjected to three conversational scenarios: visual (gestures without sound), auditory (sound without lip movement) and audiovisual (gesticulation and sound); patients with cataracts showed less activity in both auditory and visual areas during the three stages.

The role of vision in language is clear because it connects words and images. The information derived from visually recorded language corresponds to the gestures produced by the interlocutor, which is pivotal for language development. (15,43) Stimulus is captured by the retina and sent to the primary visual cortex, while connections that send information through the dorsal and ventral streams are simultaneously established. The ventral stream, and its occipital-temporal connections, are responsible for conceptually processing images and, in this case, provide meaning to the gestures based on emotions or spoken words.

On the other hand, the dorsal stream, with its occipital-parietal connections, is in charge of processing the perceived gesture, which, at very early stages, is considered as the raw material of articulation imitation patterns and, subsequently, of speech motor control. One example is given by doctors Hickok and Poeppel, in which an individual perceives the gesticulation of the word "cat", pronounced by its interlocutor; visual information provides a phonetic correlation to the acoustics of the word, the dorsal stream provides information of the segmentation of the word (the word contains the sound |k|) and the ventral stream contributes to the understanding of the word (domestic feline). (2,44,45) These circuits also allow recognizing the elements of the environment being designated and located in space. (12,35,45)

From a functional point of view, and regarding the emotional correlation of language, visual information is also the gateway for activating mirror neurons and, therefore, for the relationship between language and the so-called theory of mind. (46,47) According to this theory, the mirror neuron system, based on the perception of the interlocutor gesticulation, provides the individual with the ability of inferring their emotional content and act accordingly; in other words, the individual is allowed to generate empathy with the speaker. (47)

The role of vision in the development of language in individuals with visual deprivation has also been addressed. Some case series, as those reported by doctors James and Stojanovik, have characterized the changes in processing and communication skills of children with visual impairment. Such cases show children who tend to score below the tenth percentile in the tests used to measure communication skills (Children's Communication Checklist, developed by Bishop in 2003). Said tests considered the structure of language (speech, syntax, semantics and coherence), pragmatics (inappropriate opening, stereotyped language, use of context and nonverbal communication) and autistic-like behavior (restricted interests and social relations). The authors concluded that children with visual impairment have impaired language development, despite the small sample size, and the presence of other sensory deficits and associated neurodevelopmental disorders in the patients. (8) This result is similar to those reported with slightly larger samples. (48)

A more recent study published by the Kate Watkins group concluded, using fMRI, that the occipital cortex is involved in the processing of language, even in individuals with deep sensory deprivation derived from anophthalmia. (49) These studies uncover a vast area still to be developed in the relationship between the visual system and language.

## Proprioceptive information: awareness of language production

The proprioceptive stream provides the individual with information of the position of their body in relation with the environment; thus, the individual is aware of muscle tone, gravity, movement (and posture in general) and the suction-swallowing process. On a second level of proprioceptive integration, the individual is able to take over body representation and coordinate both sides of the body, showing the first signs of what will be motor planning. (11) In this regard, planning movements requires integrating visual, tactile, vestibular and proprioceptive information, which is relevant for correctly selecting the muscle groups needed for each movement and the recruitment pattern that defines the required strength. (50,51)

Several authors have established a first critical period for speech motor control development between 6 and 12 months of age. (17,52) Nevertheless, it is important to keep in mind that this process continues until adolescence, when the teenager acquires the adult pattern. (53,54) Alterations of sensory integration, including proprioceptive information, which interfere with proper motor planning, are known as developmental dyspraxia. (55)

Speech articulation also requires complex motor planning involving infralaryngeal (lungs), laryngeal, and supralaryngeal (tongue, lips) organs with a close regulation by the central nervous system. (18) To develop the motor control of speech, the infant uses visual information obtained from phonation patterns produced by interlocutors, proprioceptive information (which feeds back the used movements and allows repetition of the pattern) and auditory information that enables hearing the sounds being uttered and correlating them with the movements. (6,17,44,51) However, proving this postulate is not simple, especially when a normal scenario is used as the basis for finding a way to linearly correlate the development of motor control with language, instead of using abnormality as the starting point.

The first approaches were achieved by associating suction-swallowing disorders at very early stages and subsequent speech disorders; likewise, changes in gesticulation development, particularly evident in the second quarter of life, were also related to expressive language disorders. (56)

Nip *et al.* (51) and Nip *et al.* (57) have attempted to establish parameters of normality by describing the evolution of the orofacial gestures between 9 and 21 months of age, and relating babbling and words to the production of language afterwards. Computational analysis of facial movement has been performed to develop these studies. This work has found that this topic can be studied further to try to characterize, for example, specific changes in motor patterns from one stage of development to another. (51,57) On the other hand, Alcock made independent observations in a sample with normal language development and a sample with family alterations, concluding that there is a correlation between orofacial movement skills and the richness of vocabulary of individuals, which suggests that, although motor skills are associated with a better use of language, they are not a prerequisite. (56)

Oral proprioception has not only been correlated to expressive language development. (58) Bruderer *et al.* (53) established how sound articulation and vocalization could provide feedback and improve speech perception. These experiments were carried out in 6-month-old infants.

In short, despite research on motor control development and its correlation with language is more incipient than visual and auditory studies, it is worth noting that it is a substrate for language development. In 2007, childhood apraxia of speech was defined by The American Speech-Language-Hearing Association, as

> "a speech sound disorder in which the precision and consistency of movements underlying speech are impaired in the absence of neuromuscular deficits […] the core impairment in planning and/or programming spatiotemporal parameters of movement sequences results in errors in speech sound production and prosody". (59)

Sensory integration disorders have an impact on motor control maturation by limiting the ability of sequentially planning movement and preventing orofacial gestures and motor planning for articulation, which could lead to verbal dyspraxia in the most extreme cases. (18,60) Children with this condition may present slurred speech, vocal articulation errors, difficulty for sequencing oral movements and oral dysdiadochokinesia that also affect communication with peers and quality of life. (60)

### Social interaction: the ideal integration framework

Figure 1 presents how auditory, visual and motor control and proprioceptive information are framed by social integration. This context promotes a permanent feedback source that favors the development of comprehensive and expressive language. In consequence, social interaction has been characterized as a fundamental element in the critical period of language development. (61,62) Furthermore, certain epigenetic modifications have been described as being related to changes in the interaction pattern, inducing synaptic plasticity, and facilitating language learning. (58,61,63)

Early in life, social experience is family-dependent, as relatives provide the initial language input that the infant will recognize. They will also obtain auditory, visual and proprioceptive information from them to interpret and produce language. (61,63-67) More specifically, the family has an important influence on babbling/vocalization, word comprehension, naming, word combination and grammar. (68)

In the systematic review by Carvalho Ale *et al.* (69), the relation between language development and social behavior, with respect to family and school environment, was analyzed in children aged between four and six years. (69) Most of the studies retrieved referred to the family role and the influence of parental input on language development, measured through standardized instruments. In general, they found, both qualitatively and quantitatively, that interaction between children and their parents could favor language development, especially in semantic and lexical fields.

These findings are similar to those found by Rogers *et al.* (70). Their systematic review sought to determine which outcomes have been studied as causal effects on child language development within the field of communication sciences and disorders. In this publication, the linguistic skills and qualities of the caregiver are highlighted, as well as the role that therapeutic interventions exert on the language input that children receive.

## Conclusion

In language development, effective integration of the auditory, visual and proprioceptive information at very early stages of neurodevelopment is fundamental. The importance of each system is evident when the individual lacks the information that they separately provide, either caused by sensory deprivation, as in the case of auditory and visual input, or by a deficit in articulation and motor phonation planning processes due to alterations in proprioceptive afferents and motor efferent of the orofacial muscles. The effect on language development is worse if that occurs earlier at critical periods.

The principles of sensory integration were presented in this review as decisive for language development, which offers not only a way to understand this complex process from an evolutionary perspective, but a proposal to address deviations. The research undertaken in this regard should aim at delving into the current knowledge on how the integration of auditory, visual and proprioceptive information occurs, as well as at strategies that allow, on the one hand, early detection of subtle alterations in this process and, on the other, establishing timely interventions on these deviations.


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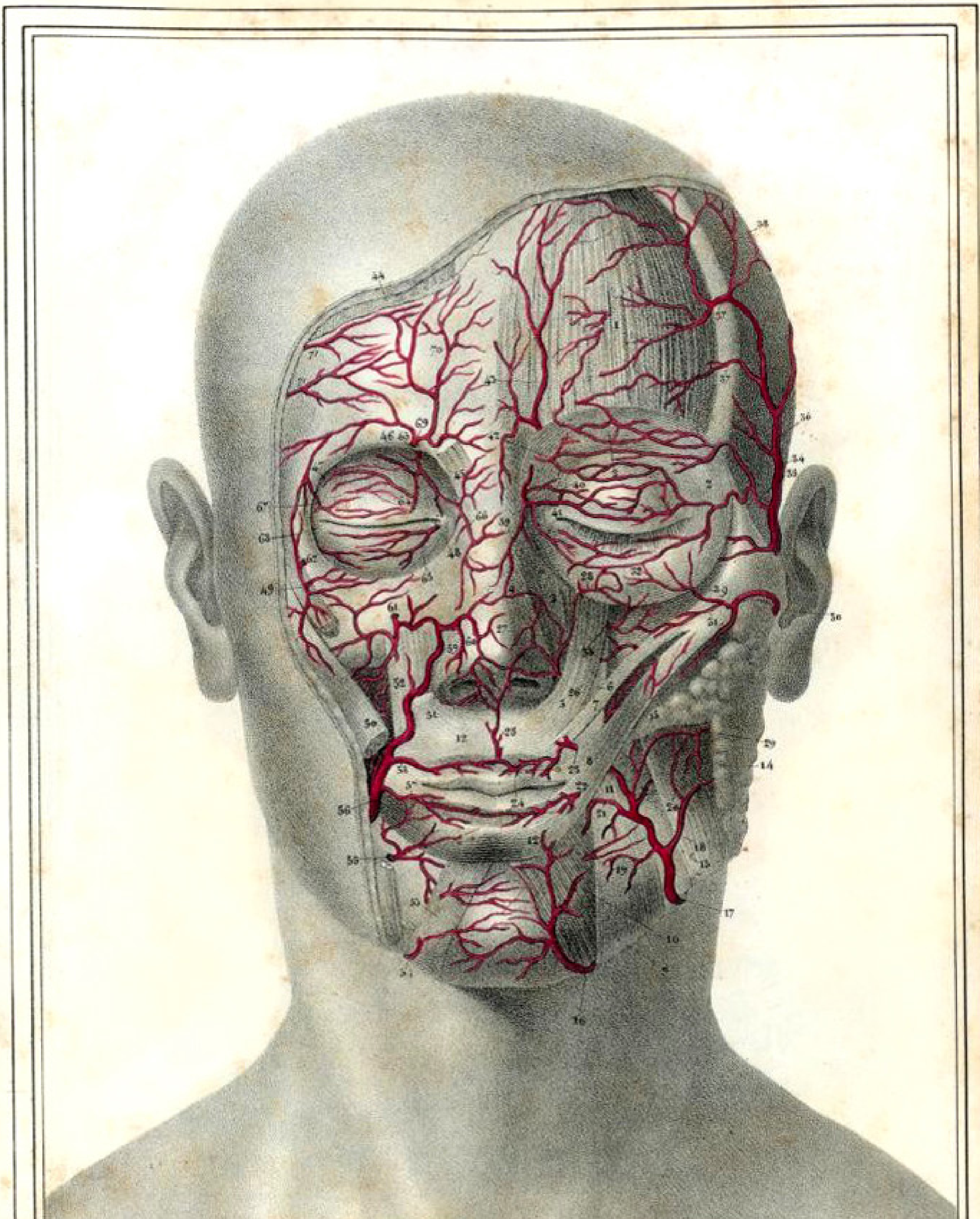

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