Journal of Bioanthropology

ISSN 2787-8201 (Online)
UDK 572
vol. 4, no. 3 (2024)
https://doi.org/10.54062/jb

INSTITUT ZA ANTROPOLOGIJU
INSTITUTE FOR ANTHROPOLOGICAL RESEARCH

Journal of Bioanthropology

Publisher: Institute for Anthropological Research

Address: Ljudevita Gaja 32, 10000 Zagreb, Croatia

Mail: editors@inantro.hr

Web page: https://inantro.hr/en/journal-of-bioanthropology-2/

First publication: december 2021

Frequency of publication: semi-annually

ISSN 2787-8201

UDK 572

DOI https://doi.org/10.54062/jb

Cover image taken with the permission of the Organizational Board of the 23rd EAA Congress held in Zagreb in September 2024.

About the journal:

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IAR Publishing

Journal of Bioanthropology

Volume 4, 2024. p. 4-5

ISSN 2787-8201; UDK 572

A Milestone in European Anthropology — Zagreb Hosts the EAA Congress for the Fourth Time

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Seventh Issue July 15th, 2025

Editorial

In September 2024, Zagreb once again became a focal point of anthropological scholarship as the city hosted the 23rd Congress of the European Anthropological Association (EAA), held in parallel with the 16th Scientific Meeting of the International Society for the Study of Human Growth and Clinical Auxology (ISGA). This joint congress, entitled *"Anthropology in the Anthropocene: Investigating Human Influences on the Global Ecosystem,"* was convened at the Faculty of Kinesiology, University of Zagreb, from 5 to 7 September. The event was organized under the auspices of the Institute of Anthropology in Zagreb.

Bringing together scholars from diverse disciplines like evolutionary biology, biomedicine, epidemiology, genetics, archaeology, and biological anthropology, the congress served as a dynamic platform for presenting the latest advances in the understanding of human health, development, and the anthropological implications of the Anthropocene epoch. Its interdisciplinary nature reflected the increasingly integrative approach required to tackle complex questions concerning human adaptation, variability, and impact on global ecosystems.

Continuing a Legacy of Scientific Engagement

The 2024 meeting marked the fourth time that Zagreb has hosted the EAA Congress, underscoring the city's long-standing relationship with European anthropological scholarship. The inaugural EAA Congress was held in Zagreb in 1977, and subsequent meetings in 2002 and 2016 further solidified the Institute for Anthropological Research's role as a key note in the European anthropological network. Founded in 1976, the EAA has been instrumental in fostering collaboration and advancing research across subfields, and its return to Zagreb in 2024 was both a recognition of the Institute's scientific leadership and a reaffirmation of Croatia's place on the map of international science.

Scientific Highlights and International Participation

The congress featured a distinguished lineup of keynote speakers, including Prof. Kate E. Pickett (University of York, UK), Prof. Jana C. Semenza (Umeå University, Sweden & University of Heidelberg, Germany), Prof. Eörs Szathmáry (Eötvös University, Hungary), Prof. Noel Cameron (Loughborough University, UK), Prof. Tim Cole (University College London, UK), Prof. Emanuela Cristiani (Sapienza University of Rome, Italy), and Dr. Maito Metspalu (Institute of Genomics, University of Tartu, Estonia). Their presentations offered cutting-edge insights into pressing issues ranging from evolutionary theory and genomics to social inequality and public health.

Notably, Croatian scientists also played a central role, with Prof. Dr. Sanja Musić Milanović and Prof. Dr. Davor Štimac addressing the growing burden of childhood obesity, one of the most pressing public health challenges of our time.

Joint Collaboration with ISGA

For the first time, the EAA Congress was held jointly with the 16th Meeting of the International Society for the Study of Human Growth and Clinical Auxology (ISGA), a society founded by James Tanner, a pioneer in human growth research. This collaboration reflected

the natural synergy between the two fields, facilitated by a shared focus on human biological development and health across the life course. The decision to convene both meetings concurrently in Zagreb was a testament to the organizational capacity and international engagement of the Institute for Anthropological Research.

The congress was officially opened by the Assoc. Prof. Dr. Saša Missoni, Chair of the Organizing Committee and Assistant Director for International Cooperation at the Institute for Anthropological Research. The opening keynote was delivered by Prof. Dr. Dragan Primorac, a leading Croatian authority in personalized medicine.

Disseminating Scientific Contributions

In recognition of the high scientific quality of the congress contributions, the Institute for Anthropological Research is proud to support the dissemination of full-text papers in its affiliated journal. This initiative reflects the commitment to not only fostering academic exchange during the congress itself but also ensuring long-term visibility and impact for the research presented.

As the Anthropocene continues to challenge our understanding of human-environment interaction, events such as the 23rd EAA and 16th ISGA Congress provide essential forums for critical reflection, scientific advancement, and interdisciplinary collaboration. Zagreb's role as host once again reinforces its enduring contribution to the field of anthropology.

Dr. Mario Novak, senior research associate

Lucija Dodigović, head of the library of the Institute for Anthropological Research

IAR Publishing

Journal of Bioanthropology

Volume 4, 2024. p. 6-23

ISSN 2787-8201; UDK 572

https://doi.org/ 10.54062/jb.4.3.3

Morphological Development and Maturity Assessment of the Coracoid Process and its fusion site on the glenoid-coracoid interface.

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Received November 14th, 2024
Accepted for publication February 6th, 2025
Online First February 20th, 2025

Keywords: Coracoid process, metaphysis, geometric morphometrics skeletal maturity.

Abstract

This study investigates the morphological changes of the coracoid process and its metaphyseal surface at the glenoid-coracoid interface, aiming to characterize these transformations across different maturity stages. A total of 26 coracoid epiphyses and 48 coracoid metaphyses from a skeletal sample excavated at the medieval Dominican Convent of San Pablo in Burgos, Spain, were analysed. The sample was 3D scanned and divided into four distinct maturity groups based on developmental criteria. Utilizing three-dimensional geometric morphometric analysis, two different 3D template configurations were created to capture the shape changes during the development of the coracoid process and its metaphysis, respectively. The analysis included Shape and Form space analysis, allowing for an evaluation of maturity transitions and their interrelationship with size. The research identified the first principal component, both in Shape and Form Spaces Analysis, as the most suitable for elucidating ontogenetic changes in both shape and form. The findings demonstrate a clear, coordinated progression of the coracoid process and coracoid metaphysis morphology from childhood to adolescence, indicating that the morphological changes of the articular surfaces of the coracoid epiphysis influence the changes in the metaphyseal surfaces. By correlating these changes, the study infers potential new methods for estimating skeletal maturity in dry bone contexts. Moreover, this research emphasizes the significance of both size and shape variations in assessing skeletal maturity, with shape differentiation playing a more prominent role in later developmental stages than size. Ultimately, this study contributes to a deeper understanding of skeletal growth patterns and offers valuable insights for refining age estimation methodologies, particularly in anthropological and forensic contexts.

Introduction

Constructing age distributions from skeletal remains is a critical aspect of anthropological research. The most reliable methods for estimating the age of non-adult individuals are based on dental development (Liversidge, 2008). However, suitable dental material is not always available, making it necessary to explore alternative methods. In such cases, the diaphyseal growth in the length of long bones is considered a valuable approach for age estimation, particularly in preadolescent individuals (Cardoso et al., 2014).

Several predictive equations have been developed based on different modern samples, each with varying growth patterns, body sizes, and proportions, to estimate age from diaphyseal lengths (Cowgill et al., 2010; Rissech et al., 2008, 2013; Lopez-Costas et al., 2012; Cardoso et al., 2014; Stull et al., 2014). Additionally, though less frequently, some studies have also incorporated measurements of the clavicle and scapula, focusing on increases in their length and width. (Rissech and Black, 2007; Cardoso et al., 2017). In all cases, choosing the correct predictive equation for age estimation is crucial to obtain an accurate estimation. An effective way to choose the appropriate equation is by assessing bone size in relation to its maturity or skeletal development, as is commonly done in clinical settings. Although, skeletal age can be influenced by factors such as sex, nutrition, metabolic and genetic conditions, and social circumstances (Cavallo et al., 2021), generally, while individuals showing an advanced skeletal development, while tall for their chronological age, tend to be short for their skeletal ages, individuals showing a delayed skeletal development, are short for their chronological age but tall for their skeletal age (Martin et al., 2011; Bayley 1946). Therefore, the combined assessment of ages obtained through different prediction equations based on long bones and those derived from skeletal development is essential for achieving an accurate estimation.

The process of maturity involves both quantitative and qualitative changes that transform an undifferentiated, immature state into a highly organized, specialized, and mature state (Roche, 1992). The assessment of skeletal maturity is based on a series of indicators that are discrete events or recognizable states within the continuous process of maturation (Cameron, 2004). Several methods have been developed based on maturity indicators that describe the sequence of the onset of ossification in the epiphyses of the long bones, the changes in shape and size of the epiphyses, the chronology of the epiphyseal union, and the percentage of adult size achieved (Eveleth and Tanner 1990; Humphrey 2003).

In bioarcheological contexts is very common the use of standards charting the chronology of unions of epiphyses to diaphyses for age estimation (Stevenson 1924; Todd1930; Stewart 1934; Coqueugniot and Weaver 2007; Schaefer and Black 2007; Cardoso2008, b; Cardoso and Ríos 2011; Cardoso et al. 2014). However, these standards are restricted to a concrete period of life, as their utility is limited to pre-adolescents and adolescents.

This has led several authors to explore the application of indicators based on changes in the shape and size of the epiphyses, which can be tracked throughout the entire development period (Conceição and Cardoso, 2011; García-González et al., 2019). Additionally, there are studies focused on defining maturity states based on metaphyseal changes (García-González et al., 2024a; Salazar-Fernández et al., under review). All of these have proven useful for assessing the maturity status of archaeological individuals, as well as for age estimation. Thus, it is reasonable to continue adapting or developing methods based on maturity indicators that can be applied through direct observations of dry bones. In this context, the scapula is a strong candidate. Unlike long bones, which grow primarily in length through two metaphyses (proximal and distal), the scapula develops through multiple metaphyseal areas. It has at least seven secondary ossification centres and one primary ossification centre (Cardoso, 2008; Ogden & Phillips, 1983). These centres include the articular base of the glenoid-coracoid interface, the inferior angle, the vertebral border, the acromial process, the glenoid rim, and the apex and angle associated with the coracoid process (Kothary et al., 2014; Scheuer & Black, 2004). Most of these ossification centres appear, form, and fuse during adolescence. The scapula, like other flat bones, is highly fragile. Consequently, in archaeological contexts, only its thicker parts, such as the glenoid cavity, coracoid process, or spine, are often recovered. This limits the ability to estimate age at death based on the main dimensions of the scapula. Existing studies on non-adults, such as those by Ogden & Phillips (1983) have concentrated on the global ossification of the scapula and how various pathologies and traumas impact its development, as observed through radiographic data. Similarly, Kothary et al. (2014), examined the presence or absence of the ossification centres that compose only the glenoid and the glenoid-coracoid interface, using a sample analysed

through magnetic resonance imaging (MRI). Unfortunately, radiographic studies on the scapula are limited due to visualization challenges within the appendicular skeleton (Ogden & Phillips, 1983). Furthermore, such studies are difficult to extrapolate to dry bone samples. Yet, García-González et al. (2024a), have shown that developmental changes in the scapular glenoid cavity can be a valuable tool for estimating age at death. Although this study focused on the maturity changes at the fusion site of the coracoid process, there has not been an extensive assessment of its overall developmental process. Therefore, more exhaustive research on the ontogenetic changes associated with scapular ossification is necessary to better understand its developmental complexity in dry bone samples. Most of the secondary ossification centres of the scapula appear, form, and fuse during adolescence (Scheuer et al., 2004). However, the coracoid process undergoes a prolonged process of skeletal maturation, from its initial appearance to its fusion in adolescence, making it an epiphysis with a longer developmental timeline compared to other scapular epiphyses. While the coracoid process is often considered a primary ossification centre due to its potential formation during prenatal development, unlike secondary centres that always appear postnatally, it behaves more like a secondary centre as it fuses postnatally (Scheuer & Black, 2000). Therefore, given its prolonged developmental period and the fact that it is recognizable early in this process, the coracoid process can be useful for skeletal age estimation.

In this study, the morphological changes of both the coracoid epiphysis and its metaphyseal interface on the glenoid-coracoid interface are analyzed using geometric morphometrics, a method well-suited to analyze and quantify the shape of biological structures through spatial coordinates (Bookstein, 2018; Mitteroecker et al., 2013, 2022; Mitteroecker & Gunz, 2009). Unlike traditional techniques that measure lengths, areas, or volumes, geometric morphometrics allows for the consideration of the geometry and spatial relationship between landmarks in a structure (Bastir et al., 2013; Gunz & Mitteroecker, 2013; Zelditch, 2004).

Materials and methods

Sample Selection and Group Classification

This study investigated 26 coracoid epiphyses, and 48 metaphyseal surfaces for the fusion of the coracoid on the glenoid-coracoid interface from non-adult skeletal remains excavated at the Dominican Convent of San Pablo in Burgos, Spain. The burials at the Convent cover a wide chronological range from the 13th to the late 19th century, but this research specifically focuses on remains dated from the 14th to the 18th centuries (García-González et al., 2024b). All individuals were carefully selected to exclude any exhibiting deformation or visible pathology.

Ages of the non-adult individuals from this collection were estimated based on the calcification and formation of their dental crowns and roots (García-González et al., 2024). Mineralization stages for each tooth type were analyzed using 3D volume renderings obtained from CT scans. The developmental stages of the permanent dentition were scored according to the method established by Demirjian et al. (1973) and subsequently converted into age estimates using the adjusted prediction data proposed by Liversidge et al. (2006). For deciduous teeth, the method developed by Liversidge and Molleson was applied (2004).

The total sample was divided into four maturity groups based on both the pattern of human growth and development by Bogin, (2021), and the specific pattern of scapular development as described by Kothary et al. (2014), Ogden and Phillips, (1983), and Scheuer et al. (2004). Radiographic evidence indicates that while the coracoid process may emerge prenatally, it is typically first observed at around 3 months of age postnatally, and is consistently present by the end of the first year of life. The coracoid process begins a marked expansion around 2 years of age, establishing a true bipolar growth region between the glenoid and the glenoid-coracoid interface, which reflects the developmental independence of the main scapular body and the coracoid (Figure 1). Consequently, our initial maturity group is set at 3 years of age, a stage at which the coracoid process has attained clear and easily recognizable morphological features.

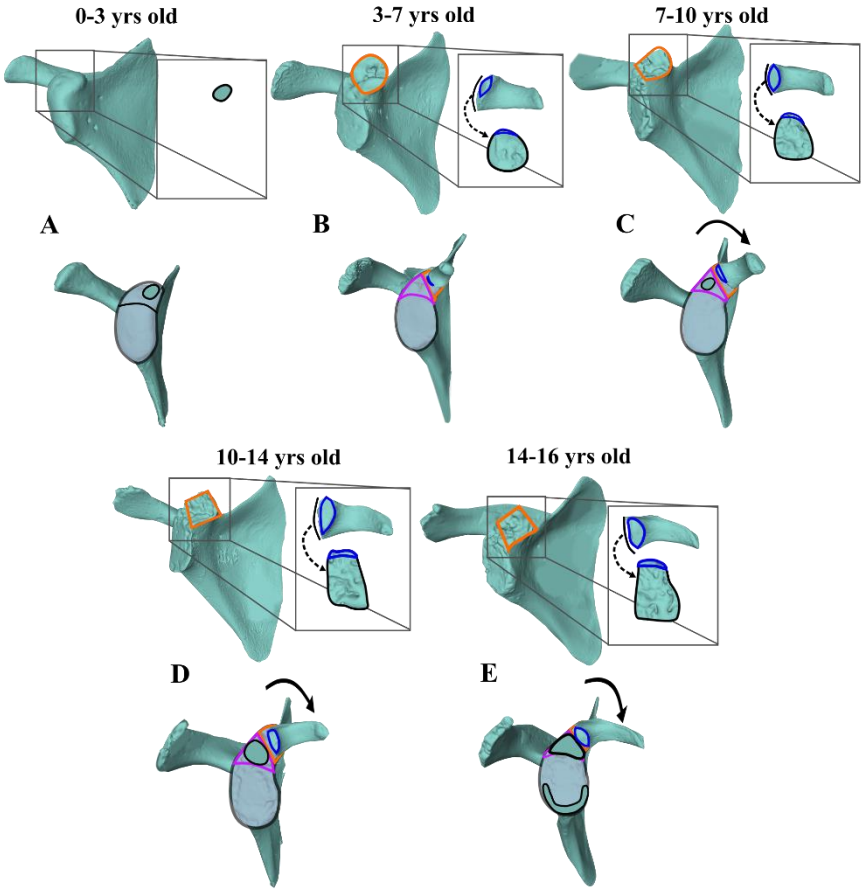

Figure 1: Developmental sequence of coracoid and glenoid-coracoid interface in antero-lateral view (upper) and lateral view (bottom)

a: Coracoid and glenoid-coracoid between birth and 3 years old,

b: appearance and initiation of the coracoid ossification centre,

c: the coracoid and its metaphysis in the glenoid-coracoid interface are morphologically recognizable,

d: extension of the subcoracoid and rotation of the coracoid metaphysis in the glenoid-coracoid interface towards anterior,

e: the coracoid process completes formation before its fusion with the subcoracoid.

This group encompasses the entirety of childhood, concluding at 7 years of age. During this developmental stage, the sole ossification event observed in the scapula pertains to the continued formation and maturation of the coracoid process. The second maturity group comprises individuals aged 7 to 10 years, representing the prepubertal and pubertal stages. Specifically, between 8 and 10 years, the first secondary ossification centre of the scapula, known as the subcoracoid, emerges. This centre is located dorsally to the base of the coracoid process and is responsible for the formation of the upper third of the glenoid cavity. The third group, consisting of individuals aged 10 to 14 years, represents early adolescence. The fourth group, including those from 14 to 16 years old, represents intermediate adolescence. This period concludes with the final fusion of the subcoracoid and coracoid processes to the scapular body. Initially, fusion occurs between the subcoracoid and coracoid processes, and once united, they briefly fuse with the body of the scapula. These maturity stages, along with their most probable age ranges of occurrence and the number of individuals used for each are depicted in Table 1.

Table 1. Maturity groups for the development of coracoid and glenoid-coracoid interface.

Maturity group	Age range	NC	NM	Definition
1 (Childhood)	3-7	6	15	The glenoid and the glenoid interface are separated by a bipolar growth plate
2 (Prepubertal)	7-10	7	10	First radiographic appearance of the subcoracoid.
3 (Early Adolescence)	10-14	6	10	The subcoracoid centre expands, covering a substantial portion of the metaphysis at the glenoid-coracoid interface.
4 (Intermediate Adolescence)	14-16	7	13	Preparation and initial fusion of the coracoid with the subcoracoid, which once united, fuse with the glenoid-coracoid interface at the final stage.

Data processing and 3D geometric morphometric Analysis.

All individuals were scanned with a 3D structured light white surface scanner, which employs trigonometric triangulation to capture surface light patterns, creating a precise 3D representation of each subject's surface. The device utilized was the EinScan Pro (Shining 3D Tech. Co., Ltd., Hangzhou, China), operated in fixed mode with an automated turntable, and controlled via EinScan Pro software (Solid Edge SHINING 3D Edition). Each scan achieved an accuracy of 0.04 mm and was obtained from 30 different angles, ensuring comprehensive 360-degree coverage. Following acquisition, all scans were aligned and merged to produce a cohesive 3D model. These models were then exported as. ply files to Meshmixer software (Co. Autodesk, Meshmixer, USA) for post-processing, addressing minor defects such as closing surface holes.

Two 3D template configurations were developed to characterize the morphology of the coracoid process and the metaphyseal coracoid surface of the glenoid-coracoid interface. These templates were applied across all the corresponding three-dimensional samples. The coracoid process template consists of 10 fixed landmarks and 77 curved semilandmarks, while the metaphyseal coracoid surface template comprises 4 fixed landmarks and 20 curved semilandmarks (Figure 2) (Table 2 and 3).

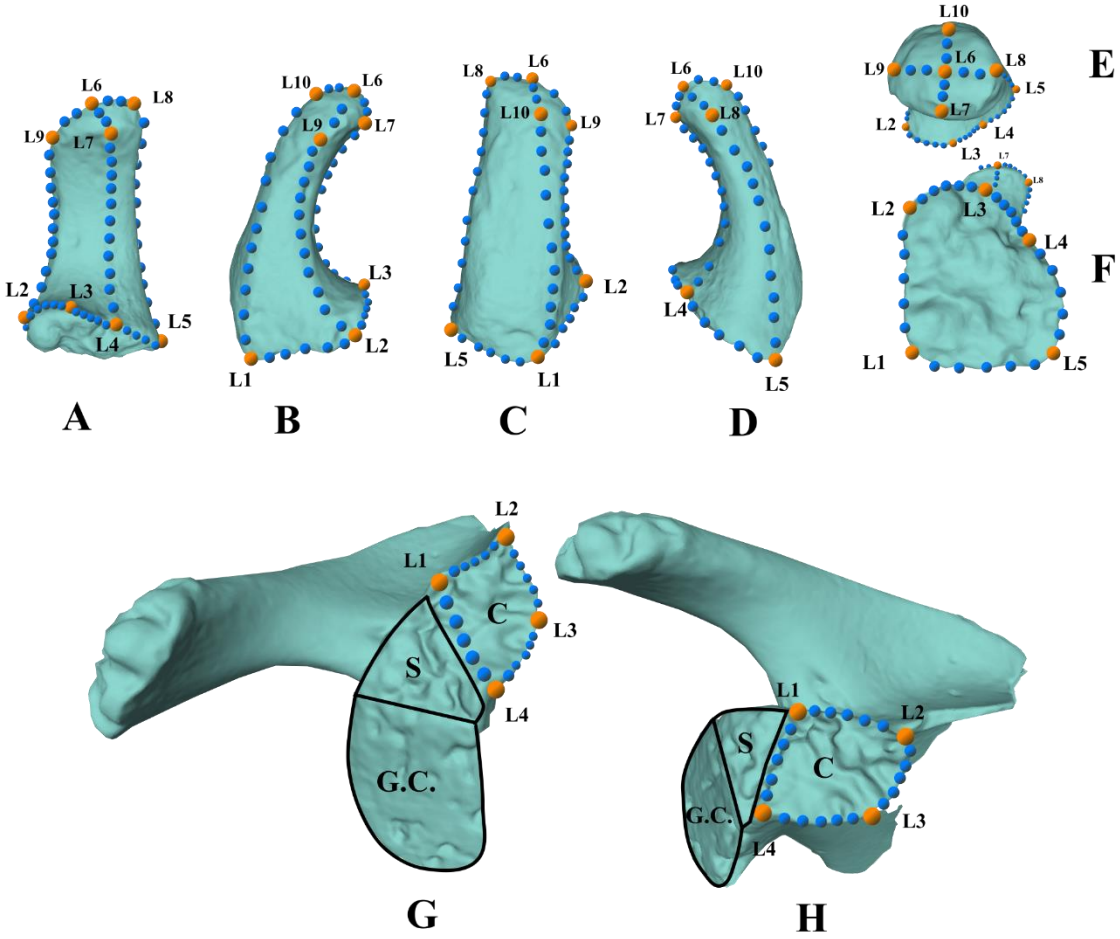

Figure 2: Set of landmarks and semilandmarks placed on the coracoid process and the coracoid metaphysis within the glenoid-coracoid interface.

Table 2. Coracoid Process Landmarks

Landmark	Description
Fixed_1	The most posteromedial point on the articular surface of the coracoid process.
Fixed_2	The most posterolateral point of the subcoracoid articular surface, located on the articulating portion of the coracoid process.
Fixed_3	The most anterolateral point of the subcoracoid articular surface, located on the articulating portion of the coracoid process.
Fixed_4	The most anterolateral point on the articular surface of the coracoid process.
Fixed_5	The most anteromedial point on the articular surface of the coracoid process.
Fixed_6	The most lateral midpoint in the apex of the coracoid process.
Fixed_7	The most posterior midpoint of the apex of the coracoid process.
Fixed_8	The most lateral point in the apex of the coracoid process.
Fixed_9	The most superior midpoint in the apex of the coracoid process.
Fixed_10	The most anterior midpoint in the apex of the coracoid process.
Curve 1	Curve between points 1 and 2. Total: 5 semi-landmarks.
Curve 2	Curve between points 2 and 3 Total: 5 semi-landmarks.
Curve 3	Curve between points 3 and 4 Total: 5 semi-landmarks.
Curve 4	Curve between points 4 and 5 Total: 5 semi-landmarks.
Curve 5	Curve between points 5 and 1 Total: 5 semi-landmarks.
Curve 6	Curve between points 5 and 8. Total: 11 semi-landmarks.
Curve 7	Curve between points 4 and 7 Total: 11 semi-landmarks.
Curve 8	Curve between points 2 and 9 Total: 11 semi-landmarks.
Curve 9	Curve between points 1 and 10 Total: 11 semi-landmarks.
Curve 10	Curve between points 7 and 6 Total: 2 semi-landmarks.
Curve 11	Curve between points 8 and 6 Total: 2 semi-landmarks.
Curve 12	Curve between points 9 and 6 Total: 2 semi-landmarks.
Curve 13	Curve between points 10 and 6 Total: 2 semi-landmarks.

Table 3. Metaphysis of the Coracoid in the Glenoid-Coracoid Interface Landmarks

Landmark	Description
Fixed_1	The most posterolateral point of the coracoid metaphyseal surface.
Fixed_2	The most posteromedial point of the coracoid metaphyseal surface.
Fixed_3	The most anteromedial point of the coracoid metaphyseal surface.
Fixed_9	The most anterolateral point of the coracoid metaphyseal surface.
Curve 1	Curve between points 1 and 2. Total: 5 semi-landmarks.
Curve 2	Curve between points 2 and 3. Total: 5 semi-landmarks.
Curve 3	Curve between points 3 and 4. Total: 5 semi-landmarks.
Curve 4	Curve between points 4 and 1 Total: 5 semi-landmarks.

Additionally, to address the uncertainty regarding landmark placement along both surfaces, semilandmarks were adjusted along their respective curves in relation to the fixed landmarks to reduce bending energy. This adjustment process was conducted first for each specimen in relation to a randomly selected template and then again against the average configuration of the sample (Bastir et al., 2013; García-Martínez et al., 2020; Mitteroecker & Gunz, 2009). Both templates were developed using Stratovan Checkpoint (Stratovan Corporation, 2020) by the same researcher (AS-F) to minimize interobserver measurement errors. Subsequently, this software was employed to apply each template configuration to its corresponding sample, further optimizing the alignment between the sample and the template and ensuring reduced bending energy (Gunz and Mitteroecker, 2013; Slice, 2006). To proceed with the analysis, the raw coordinates of landmarks and semilandmarks were imported into MorphoJ (Klingenberg, 2011) to conduct a General Procrustes Analysis (Rohlf & Slice, 1990; Slice, 2006). This analysis employed a Procrustes superimposition technique to minimize discrepancies between homologous

landmarks by adjusting their location, rotation, and scale. Therefore, size was quantified using a scaling factor known as centroid size, which is defined as the square root of the sum of the squared distances from all landmarks to their centroid—the mean of the x, y, and z coordinates for all landmarks (Klingenberg, 2016; Mitteroecker et al., 2013). This procedure transformed the raw coordinates into Procrustes shape coordinates, capturing shape information that reflects size-related differences, while excluding overall size (Bookstein, 1991; Rohlf and Slice, 1990). The Procrustes coordinates were subsequently exported to PAST 4.13 software, where a principal components analysis was performed to examine shape variations among the different maturity groups (García-Martínez et al., 2020; Gómez-Olivencia et al., 2018; Harvati et al., 2019; Harvati et al., 2024; Karakostis & Harvati, 2021; Mitterœcker & Schæfer, 2022; Morley et al., 2022).

The broken stick method was utilized to determine which principal components were statistically significant (Frontier, 1976). Considering that the development process not only consists of an increase in size (growth) but also involves a maturation process (changes in shape), and that these two processes are closely related, a form analysis was also conducted by incorporating the natural logarithm of centroid size (logCS) as an additional variable alongside the Procrustes shape coordinates (Mitteroecker et al., 2004). This approach guarantees that for isotropic landmark variation, the distribution in the size-and-shape space remains isotropic. The resulting expanded dataset, which included this additional variable, underwent a principal components analysis, allowing the distances within this broader space to be interpreted as a measure of form differences (Freidline et al., 2013; Mori and Harvati, 2019). To evaluate the degree of covariation between two sets of shape variables (the metaphysis of the coracoid glenoid-coracoid interface shape variables and the coracoid process epiphysis shape variables), we performed a two-block Partial Least Squares (2B-PLS) analysis. This method characterizes the multivariate relationships between the two shape variable blocks by identifying pairs of latent variables that maximize the covariance between them (Klingenberg, 2010; Klingenberg & Marugán-Lobón, 2013; Rohlf & Corti, 2000).

Results

Shape and Form Variation in the Coracoid Process Across Maturity Stages.

Analysis of relative warps across the entire sample yielded 25 principal components. Applying the broken stick criterion revealed that only the first four PCs were statistically significant, accounting for 61.45% of the total variance (Figure 3).

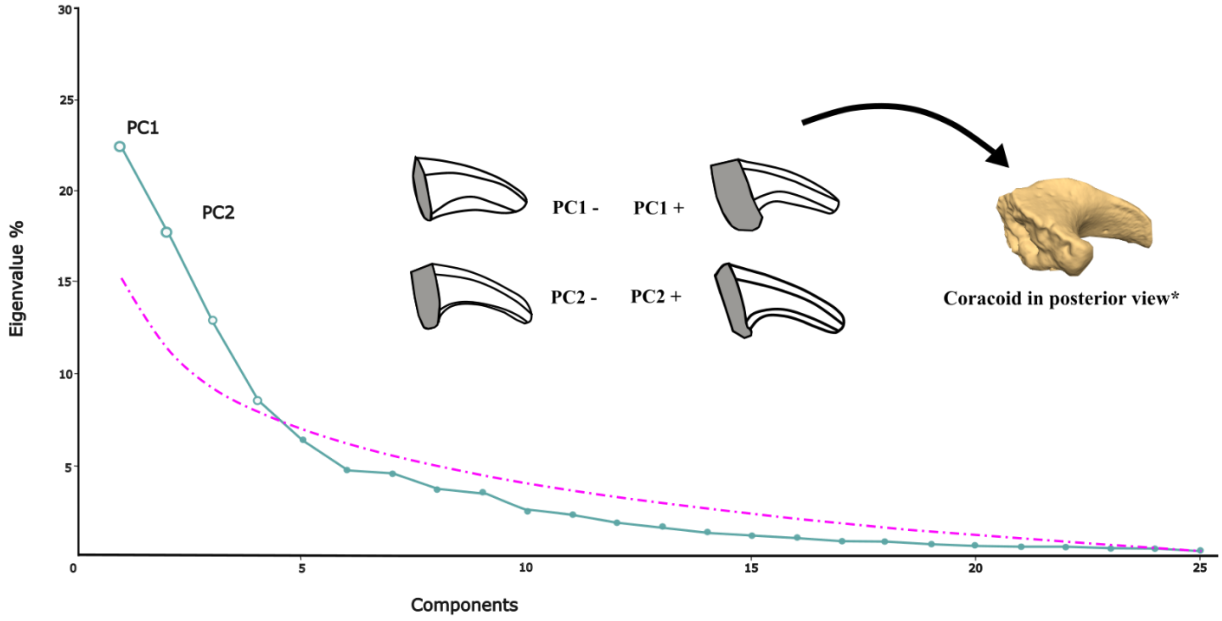

Figure 3: Principal component values obtained from the morphological analysis of the coracoid process. Broken stick values are indicated by a pink dashed line.

PC1 and PC2 explained 22.28% and 17.71% of the variability, respectively, representing a combined 39.99% of the total variance. Within the statistically significant variance, PC1 and PC2 together accounted for 65.07%. Therefore, our subsequent description of shape changes in the proximal metaphyseal surface during development focuses primarily on PC1 and PC2 (Figure 4).

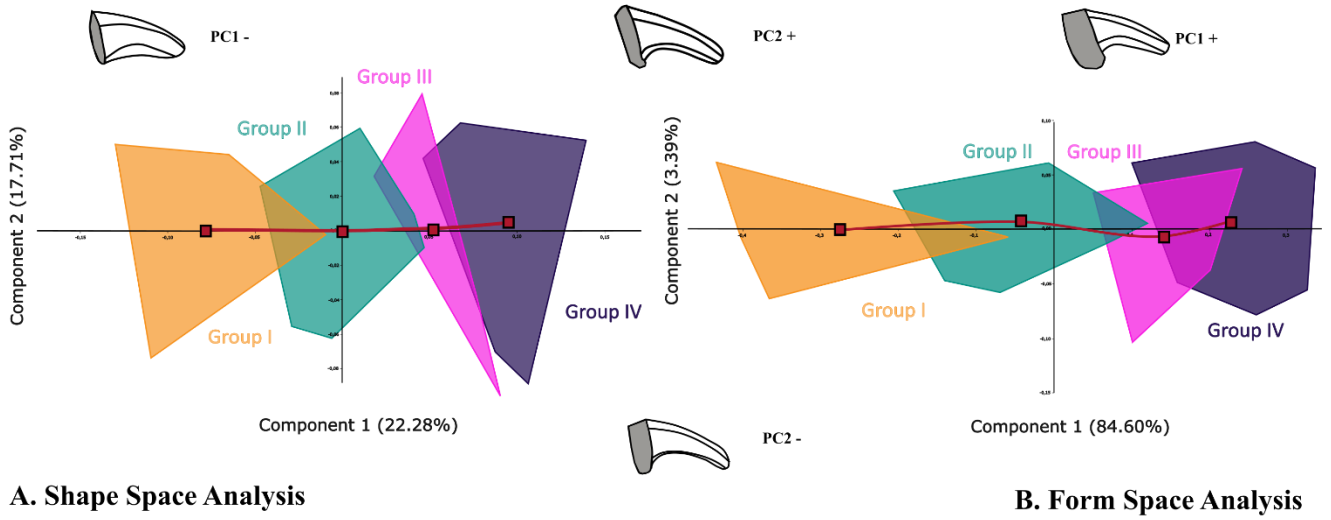

Figure 4: (A) Shape space analysis of the coracoid process, where the red line represents the mean centre of each group. (B) Form space analysis of the coracoid process, similarly, illustrating the red line as the mean centre across groups.

Shape changes along PC1 primarily reflect the transformation of the coracoid process from a short, less curved form with a rounded and flat articular base at lower values, to a significantly more curved and elongated coracoid with a quadrangular-shaped articular base with a well-defined articular area for the subcoracoid at higher values (Figure 4a). In contrast, along PC2, differences are focused mainly on the articular base. While the morphology of the coracoid body is similar across PC2, the negative values describe a slightly more curved coracoid body compared to the positive values. However, the articular base is flatter and has a less defined articular area for the subcoracoid in the negative values compared to the positive values (Figure 4a).

The first axis (PC1) shows a clear progression of groups, beginning with the youngest group, which is located at the lowest values of the axis, while individuals of more advanced ages from the skeletal sample are positioned at higher values. Thus, in the Shape Space Analysis, the first maturity group is found at the most negative values of the axis, followed by the second maturity group, which has some of its individuals in the negative section, overlapping with the highest values of the first maturity group. The other half of the second maturity group is positioned in the positive values of the axis, overlapping with the lower values of the third maturity group. Both the third and fourth maturity groups are located in the positive values, with the fourth group occupying the highest values on the axis.

The first and second principal components of the Form Space analysis account for 86.6% and 3.39% of the variance, respectively (Figure 4b). The distribution of the groups along the first principal component in the Form Space Analysis is similar to that observed in the Shape Space Analysis, but the third maturity group shows a greater degree of overlap with the fourth maturity group (Figure 4b). This suggests that the size changes are more pronounced between the first and second maturity groups, as well as between the second and third, compared to the changes between the third and fourth maturity groups.

In contrast, along PC2 (in both the Shape and Form Space Analyses) individuals from all maturity groups are distributed across both axes, showing no clear separation between them.

Given the observed shape and form changes across the positive and negative values of PC1, as well as the consecutive progression of the maturity groups along this axis, this principal component can be interpreted as representing the ontogenetic sequence. Therefore, along PC1, the shape changes corresponding to the mean values of each maturity group are as follows. In the first group, the coracoid is short and slightly curved, with a rounded and flat articular base. However, as we progress from the first to the second group, the coracoid elongates and becomes wider, while its articular base begins to lose its rounded shape. The medial portion of the base expands, and the lateral border becomes more distinctly marked for the articular area of the subcoracoid (Figure 5).

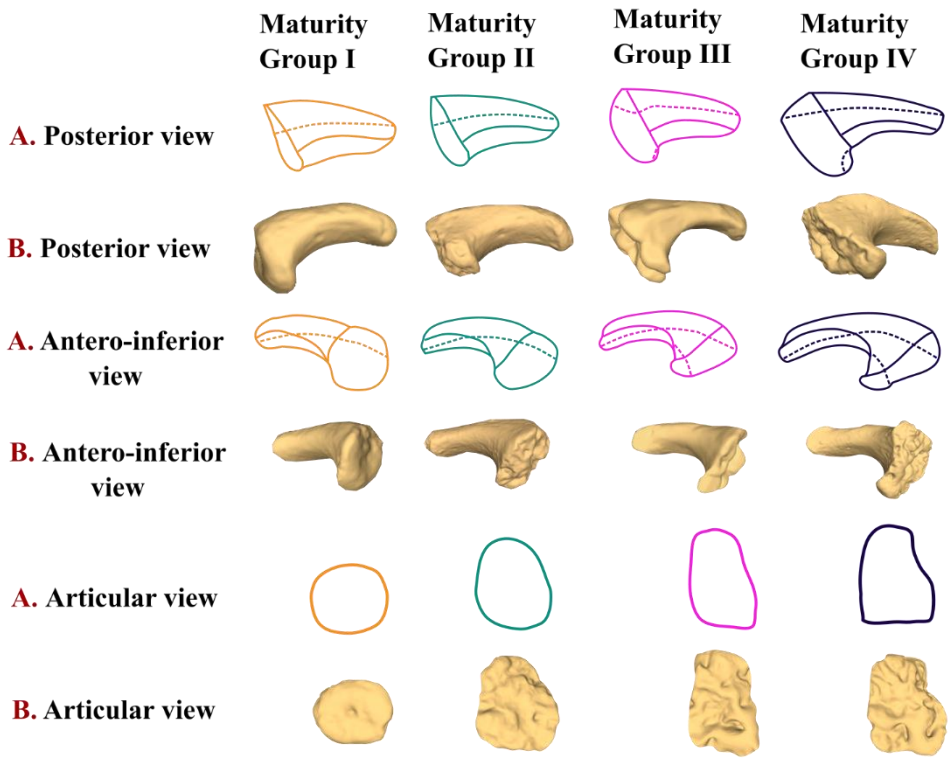

Figure 5: Ontogenetic sequence illustrating shape transformations of the coracoid process across different perspectives. Views categorized under A represent morphological changes in the coracoid process derived from mean values of maturity groups along the primary axis (PC1) in the geometric morphometric analysis. Views categorized under (B) present 3D digital reconstructions from each age cohort within the sample, serving as a comparative framework for the morphometric results shown in category (A).

In the transition from the second to the third maturity group, the coracoid body not only elongates but also appears more curved, with a more pronounced hook-like shape. The articular base elongates medially to laterally, and the articular portion of the subcoracoid becomes more expanded. The anterior part of the medial edge begins to extend more pronouncedly. Finally, in the fourth maturity group, the apex of the coracoid elongates considerably and becomes more pointed. The articular base of the coracoid has angular medial borders, and the portion of the base that articulates with the subcoracoid extends, creating a small notch on its anterior aspect that reflects the morphology of the glenoid notch positioned between the glenoid cavity and the metaphyseal interfaces of the subcoracoid and coracoid (glenoid-coracoid interface) (Figure 5).

Shape and Form Variation in the Metaphyseal Coracoid Surface of the Glenoid-Coracoid Interface Across Maturity Stages.

Principal component analysis of the entire sample yielded 47 components, of which the first five were statistically significant (based on the broken stick criterion), accounting for 72.03% of the total variance (Figure 6). PC1 and PC2 explained 25.71% and 16.16% of the variability, respectively, totalling 41.87%. When considering only the variance captured by the statistically significant PCs, PC1 and PC2 together represent 58.13% of that variance. Thus, subsequent shape analysis of the proximal metaphyseal surface during development will focus on PC1 and PC2.

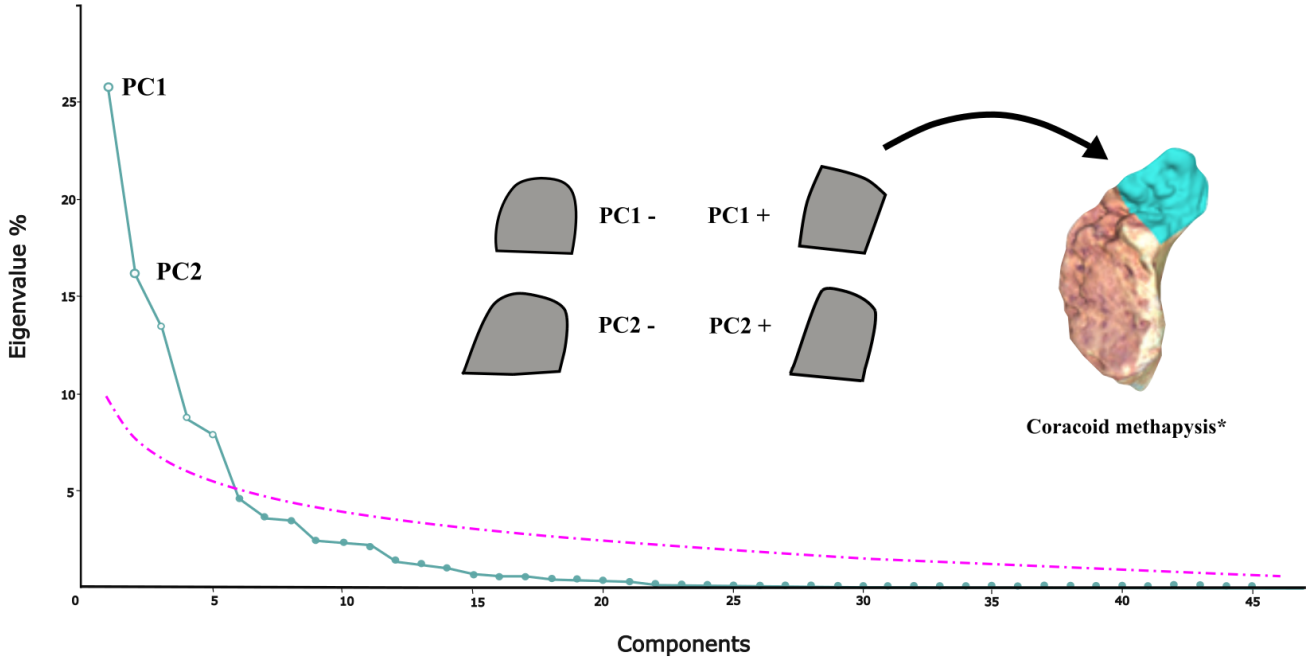

Figure 6: Principal component values derived from the morphological analysis of the coracoid metaphysis within the glenoid-coracoid interface. Broken stick model values are represented by a pink dashed line.

In the shape space analysis, PC1 reflects the morphological transformation of the glenoid-coracoid metaphysis, shifting from a short, rounded, and flat shape at lower values to a quadrangular surface tilted towards the antero-inferior plane at higher values. In contrast, PC2 captures changes in the proportions of the metaphyseal interface, transitioning from a narrower yet longer metaphysis at more positive values to a wider-than-long metaphysis at negative values.

PC1 in the Shape Space Analysis clearly separates individuals by maturity group, with younger individuals concentrated at lower values and older individuals at higher values. The youngest individuals (the first maturity group) are situated at the most negative values, while maturity group 2 is distributed around zero, with roughly half of its members in the negative range and half in the positive. Maturity group 4 is located in the positive values and maturity group 5 is located at the highest positive values. The clearest separation is observed between maturity groups 1 and 2, while groups 4 and 5 show some small overlap (Figure 7a). The Form Space Analysis reveals that the first principal component accounts for 80% of the variance, while the second principal component accounts for 7.38% (Figure 7b). Compared to the Shape Space Analysis, PC1 shows greater overlap among the last three maturity groups. The first group is situated at the lower values of the PC1 axis, while the second group has most of its values in the negative part of the axis.

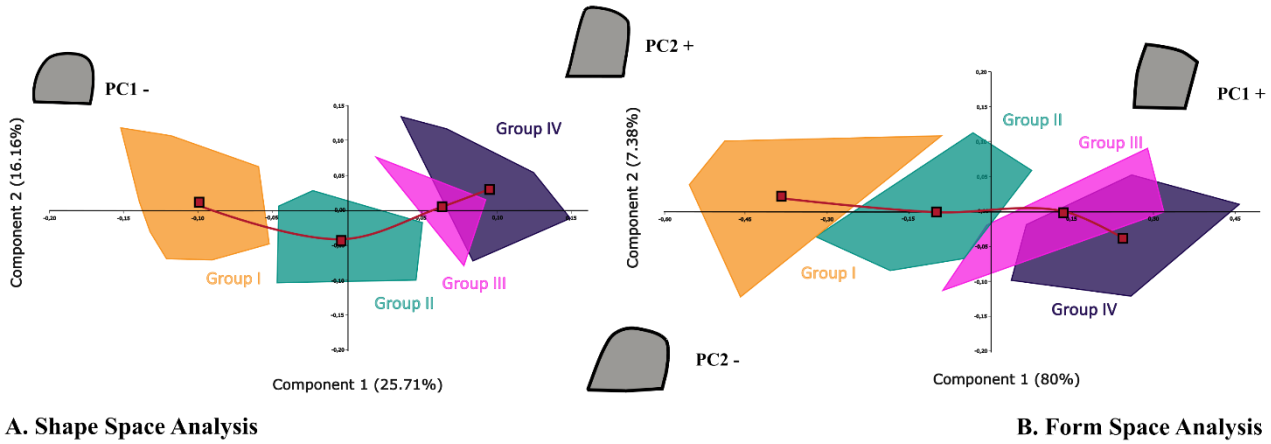

Figure 7: (A) Shape space analysis of the coracoid metaphysis within the glenoid-coracoid interface. The red line across groups indicates the mean centre of each group. (B) Form space analysis of the coracoid metaphysis in the glenoid-coracoid interface, with the red line representing the mean centre across groups.

The positive values of the second group overlap with the lower values of the third group, and the third and fourth groups demonstrate the greatest degree of overlap.

As with the analysis of the coracoid process, the distribution of individuals along PC2 shows no clear separation between maturity groups in either the Shape or Form space analysis (Figure 7). Therefore, once again, the clear progression of maturity groups along PC1 and their associated shape changes, indicates that PC1 is the axis that explains the ontogenetic sequence of the sample. Along PC1, the changes in the shape of the coracoid methapysis at the glenoid-coracoid interface are as follows, In the first maturity group, the metaphyseal surface is characterized by being short, flat, and with a rounded medial border (Figure 8). However, in the second maturity group, the medial border becomes more expanded. Additionally, the posterior border begins to elevate and develop superiorly, beginning to twist slightly toward the infero-anterior plane. Upon reaching the third maturity group, the medial border develops a quadrangular morphology. At this stage, a full torsion of the entire metaphysis toward the infero-anterior plane becomes evident.

Transitioning to the fourth maturity group, there is a pronounced mediolateral elongation and a much more pronounced torsion of the entire metaphysis of the coracoid at the glenoid coracoid interface toward the antero-inferior plane, resulting in a deeply curved glenoid notch situated between the metaphyseal interface of the inferior two-thirds of the glenoid cavity and the glenoid-coracoid interface surface (Figure 8).

Integration of the metaphyseal surface of the coracoid in the Glenoid-Coracoid Interface and the Coracoid Process Epiphysis.

The results of the 2B-PLS analysis show that Axis 1, with a singular value of 2.303×10^8, accounts for the entirety (100%) of the covariation between the two data blocks: the metaphyseal surface of the coracoid at the glenoid-coracoid interface and the coracoid process epiphysis. This finding indicates an exceptionally strong and well-defined relationship between these two structures, reflecting highly coordinated shape variation.

In contrast, the singular values for the remaining axes (Axis 2 and beyond) are negligible (< 0.001), suggesting that these axes capture only a minor fraction of the covariation. This pattern highlights that the first axis effectively encompasses almost all the shared variation, with subsequent axes likely representing noise or biologically insignificant variations.

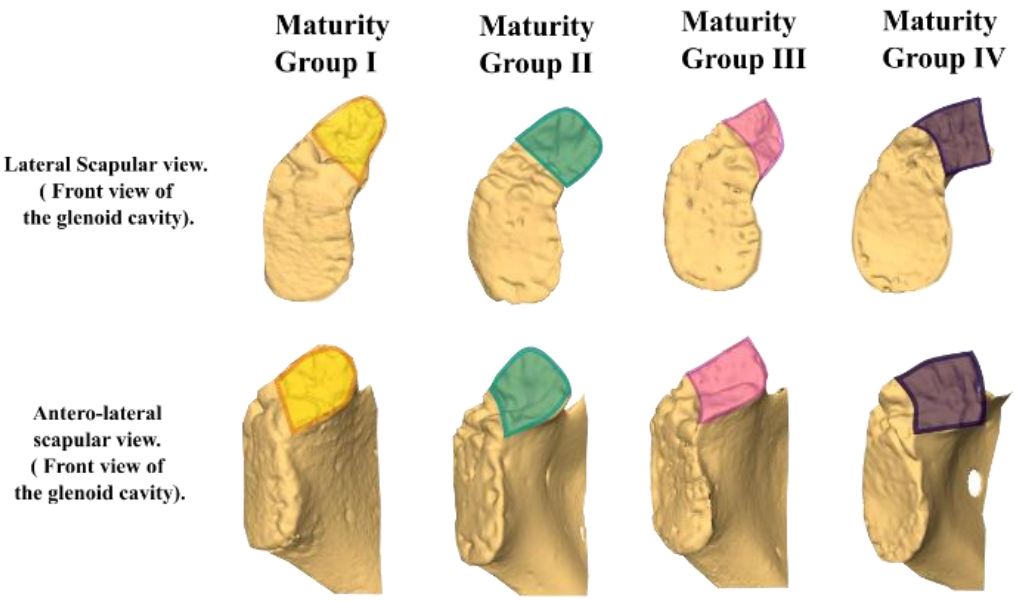

Figure 8: Sequence of shape changes in the coracoid metaphysis within the glenoid-coracoid interface, derived from geometric morphometric analysis and overlaid on 3D models of the sample, corresponding to each maturity group.

Discussion

This study investigates the application of 3DGM to assess maturity changes in the coracoid process and its corresponding fusion site on the glenoid-coracoid interface. The shape transformations described by PC1 in both Shape and Form spaces provide a framework for understanding the maturation sequence of the coracoid process and its glenoid-coracoid fusion site.

Our findings reveal parallel morphological changes between the articular base of the coracoid process and its corresponding metaphysis within the glenoid-coracoid interface throughout skeletal development. Ogden and Phillips (1983) previously observed that the coracoid expansion around age 2 significantly influences the structural maturation of the glenoid-coracoid interface, fostering the establishment of a true bipolar growth interface. From the end of infancy onward, the coracoid epiphysis acquires a more complete morphology, which facilitates a detailed examination of its skeletal developmental trajectory. The developmental sequence in our study begins with the first maturity group, encompassing the complete childhood period from 3 to 7 years (Bogin, 2021). During this stage, the coracoid process is presented as short and slightly curved, with a rounded, flat articular base, while its associated metaphysis at the glenoid-coracoid interface shares a similarly short, flat, and rounded morphology. Throughout childhood, ossification changes in the scapula remain minimal, apart from the progressive replacement of epiphyseal cartilage along the vertebral border through advancing endochondral ossification (Rissech & Black, 2007). The only ossification event isolated from the scapular body during this period pertains to the continued and gradual development of the coracoid process (Kothary et al., 2014).

At the age of 7 years old, the transition from the first to the second maturity group marks a shift from childhood to preadolescence, coinciding with the onset of the midgrowth spurt (Bogin, 2021). This event represents a modest, temporary increase in growth velocity, generally observed around this age. However, sometimes the midgrowth spurt is difficult to detect. For instance, in the study by Dos Santos et al. (2019), this spurt was observed in approximately 70% of a Portuguese sample at an average age of 6.5 years, with minimal differences between sexes. In contrast, studies such as the First Zurich Longitudinal Study of Growth identified the midgrowth spurt between ages 6.5 and 7 in girls and between ages 7.5 and 8 in boys, indicating potential sex-related differences.

The midgrowth spurt has been linked to adrenarche, a developmental phase marked by increased androgen production from the adrenal glands, which are located above each kidney (Bogin, 2021). However, as noted by Butler et al. (1990) and Sheehy, Gasser, Molinari, and Largo (1999), caution is warranted when correlating the timing of the midgrowth spurt with adrenarche. For example, Remer and Manz (2001) suggest that a significant increase in androgen secretion may occur 1 to 2 years after the midgrowth spurt, based on a sample where this spurt appeared at an average age of 6.8 years.

In terms of skeletal development, the scapula's first secondary ossification centre, the subcoracoid, typically emerges between ages 8 and 10, aligning with the timeframe of the second maturity group and coinciding with the previously mentioned events. The subcoracoid functions as a secondary centre for the coracoid itself, initially fusing with it and subsequently with the scapular body around age 16, thereby linking the coracoid process with the superior third of the glenoid cavity (Scheuer & Black, 2000). The second maturity group, spanning from 7 to 10 years, is notably influenced by the emergence of the subcoracoid center. One of the most visible morphological changes in this phase is the pronounced extension of the subcoracoid articular area on the articular base of the coracoid process, which becomes increasingly distinct. This morphological transformation, coupled with an anteroposterior extension of the medial border of the coracoid base, causes the structure to lose the rounded, smoother appearance typical of the previous age group. This change is also mirrored in the morphology of the coracoid metaphysis within the glenoid-coracoid interface, which gradually acquires a more quadrangular form. Furthermore, the posterior side of the metaphysis in the interface begins to increase towards the superior plane. This marks the beginning of a transition in the plane of the coracoid metaphysis in the glenoid coracoid of the interface towards the infero-anterior direction. Around age 10, the onset of the third maturity group signals a transition from puberty into early adolescence, a shift also influenced by gonadarche, or the activation of the gonads (Bogin, 2021). This process triggers the active production of sex hormones, which are essential not only for the development of secondary sexual characteristics but also for the significant increase in growth rate that leads to peak height velocity (PHV) (Bogin, 2021; Falkner & Tanner, 1978; Hermanussen & Burmeister, 1993; Kumanov & Agarwal 2016; Phillip & Lazar, 2003; Rogol, 2010; Tanner, 1976). Therefore, the third maturity group, encompassing ages 10 to 14, is characterized by a marked acceleration in growth velocity in both height and weight during early adolescence. During this stage, the coracoid process not only elongates but also develops a more pronounced curvature, enhancing its hook-like form. Its articular base extends medially to laterally, with a noticeable expansion along the anterior-medial border. Thus, having an extension towards the metaphyseal surface of the coracoid angle. The metaphysis at the glenoid-coracoid interface reflects these morphological adjustments in the coracoid's articular area, with the adding of an increasingly pronounced twist toward the infero-anterior plane.

In previous maturity groups, it has been established that the subchondral bone of the glenoid typically appears flat or slightly convex in an anteroposterior view. However, at the onset of the third maturity group, the subchondral bone of the glenoid gradually adopts a concave contour, becoming more similar to the articular surface. Additionally, around age 10, undulations begin to develop at the cartilage-bone interfaces of the acromion and the inferior scapular margin (Ogden and Phillips, 1983). These morphological changes are believed to be responses to alterations in the stress-strain dynamics from the surrounding musculature. In the coracoid process, a similar biomechanical response is suggested by the pronounced curvature of the coracoid body and the marked torsion observed in its metaphysis at the glenoid-coracoid interface. This morphological adaptation appears to reflect the increasing biomechanical demands and muscle mass growth characteristic of this stage of skeletal development, indicating the coracoid’s functional alignment with the evolving musculoskeletal and ligamentous system during early adolescence.

The fourth maturity group, ranging from 14 to 16 years, represents the final stage of skeletal maturity for the coracoid before its fusion. During this period, the coracoid process becomes more pronouncedly curved, and the area of its apex elongates. This transformation may be influenced by the appearance of two secondary ossification centres located at the apex and angle of the coracoid, which contribute to its structural maturation, though complete fusion is not achieved until approximately age 20. The articular surface of the subcoracoid substantially elongates as it spreads laterally, adapting to the curvature of the scapular notch's morphology in the anterolateral region (). Whereas the metaphysis of the coracoid at the interface undergoes a pronounced torsion toward anterior, aligning finally within a sagittal plane as it approaches final fusion with the epiphysis.

This sagittal reorientation serves a clear biomechanical function that becomes more active from puberty onward, supporting the stability and mobility of the shoulder complex as the surrounding musculature develops (Rockwood & Matsen, 2017). The coracoid process is a critical anatomical site for the attachment of several key muscles and ligaments essential to shoulder mechanics. Key muscular attachments include the pectoralis minor, which links the coracoid process to the thoracic cage; the short head of the biceps brachii, which extends from the coracoid to the proximal radius; and the coracobrachialis, which connects the coracoid to the humerus. Furthermore, important stabilizing ligaments attach to the coracoid, including the coracoclavicular ligaments—the conoid and trapezoid—which are vital for maintaining clavicular alignment and stability. The coracoacromial ligament, one of the primary extracapsular ligaments of the glenohumeral joint, provides crucial support against superior humeral head displacement, while the coracohumeral ligament strengthens the joint capsule, enhancing overall structural integrity (Nordin & Frankel, 2001). Together, these muscular and ligamentous attachments underscore the functional and biomechanical importance of the coracoid process within the shoulder (Gasbarro et al., 2017).

The coracoid process undergoes significant morphological changes as it approaches skeletal maturity. Initially positioned more superiorly, the metaphysis of the coracoid gradually shifts through anterior torsion, ultimately aligning the coracoid epiphysis within a more sagittal plane (Figure 1b). During adolescence, rapid skeletal and muscular growth further accentuates this torsion, and the coracoid process adopts a distinct hook shape as its apex elongates (Figure 1b).

This period of skeletal maturation is further distinguished by the development of the remaining secondary ossification centres within the scapula. The rim of the glenoid cavity and the acromion appear first, typically between ages 14 and 16. Toward the later stages of adolescence, from approximately ages 15 to 17, additional ossification centres emerge along the medial border and the inferior angle of the scapula (Scheuer & Black, 2004, 2000). This progressive scapular development strengthens the shoulder girdle and glenohumeral joint, reinforcing the biomechanical adaptations seen in the coracoid process and supporting the increased demands on the shoulder complex during this critical growth period (Mao & Nah, 2004; Villemure & Stokes, 2009).

When comparing the Shape and Form space analyses, it is observed that while in the Shape Space Analysis of the coracoid process, all the groups generally overlap to the same degree, in the Form Space Analysis the last two groups overlap to a greater degree. This suggests that while the changes in shape and size are sufficiently critical in the first two maturity groups, this is not the case for the last two maturity groups (Figure 4 and 7). Furthermore, when comparing the degree of overlapping of the last two maturity groups between the Shape and Form space analyses, it is observed that the shape variant is more divisive than the size variant. Therefore, the changes in size are more significant in the transition from the first to the second maturity group, coinciding with the mid-growth spurt, and in the transition from the second to the third maturity group, coinciding with the adolescent growth spurt. While in the transition from the third to the fourth maturity groups, the shape variant is more discriminatory than the size variant. Similarly, in the case of the coracoid metaphysis at the glenoid-coracoid interface, both in the Shape and Form Space Analyses, the first two

groups are also the most independent, especially in the shape analysis while the last two overlap, Therefore, the changes in shape and size of the first two maturity groups are more pronounced in contrast to the last two maturity groups (Figure 4 and 7).

Additionally, the results of the 2D-PLS analysis reveal a clear dominance of Axis 1 in explaining the total covariation, which underscores a functional integration and/or developmental coordination between the glenoid-coracoid interface and the coracoid process epiphysis. This shape covariation may be driven by the need to maintain shoulder joint stability or mobility. The lack of significant covariation in secondary axes supports the notion that the relationship between these structures is strongly concentrated in a single primary dimension of variation. This aligns with previous studies emphasizing modularity and integration in the evolution and development of the skeletal system

Conclusion

This study outlines a clear sequence of morphological transformations in the coracoid process and its metaphyseal interface as they progress through maturity stages, reflecting both structural development and adaptive functional changes. Comparative analysis of shape and form spaces shows that size variations are more influential in earlier growth stages, while shape differentiation plays a greater role in later stages than size, which highlights the value of geometric morphometrics in establishing shape differences independent of size variations. The observed influence of epiphyseal changes on the metaphysis supports the potential development of new methodologies for assessing skeletal maturity in dry bone contexts, especially valuable in anthropological and forensic settings where radiographic tools may be unavailable. This work provides a deeper understanding of developmental stages in dry bones, contributing to improved accuracy in skeletal age estimation.

Acknowledgements

We have benefitted from fruitful discussions with our colleagues from the Laboratorio de Evolución Humana at the University of Burgos

Grants

The Atapuerca research project is financed by MCIN/AEI/10.13039/501100011033/FEDER, UE grant number PID2021-122355NB-C31.

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IAR Publishing

Journal of Bioanthropology

Volume 4, 2024. p. 24-39

ISSN 2787-8201; UDK 572

https://doi.org/ 10.54062/jb.4.3.4

Bridging Heritage and Progress: Perspectives on Tourism Development in Gorski Kotar, Croatia

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Received January 30th, 2025
Accepted for publication March 10th, 2025
Online First March 11th, 2025

Keywords: heritage, modern infrastructure, tourism, Gorski Kotar, Croatia.

Abstract

The paper examines the paradoxical scenario of Gorski Kotar, an important Croatian transit corridor. Despite being situated in the tourism-centric county of Croatia, the region faces a notable deficiency in tourism offerings and visits. The research focuses on key elements of major infrastructure, a historic road and a motorway, to shed light on the untapped potential of Gorski Kotar's tourism sector. The Lujzijana Road, a significant cultural heritage, once served as an important link to the Adriatic ports and the coast, promoting the progress of the region and transit tourism. The construction of the modern motorway, while speeding up access to the coastal destinations, inadvertently bypasses the cultural and historical richness of Gorski Kotar, leading to a decline in tourist stopovers. The research methodology includes desk research and semi-structured interviews with local residents and roads' users, which provided insights into the challenges and opportunities in the tourism sector of the region. By examining the interplay between the human and built environment, this research attempts to bridge the gap between historical significance and modern infrastructure. It highlights how infrastructure can play a role in tourism as a tourist offer, and how infrastructure can both promote and hinder the development of tourism.

Introduction[1]

Gorski Kotar is a Croatian region that is historically rich and naturally beautiful. However, the region struggles with a significant lack of tourist offers and visits. The use of two road infrastructures in tourism is explored in this paper: The Lujzijana Road as a historic road and Rijeka–Zagreb motorway as a modern motorway; and its impacts on the development of tourism in the region. The focus of the research is on the interplay between the human and built environment and it seeks to highlight some of the issues and challenges associated with the road infrastructure and tourism development in the region. Although infrastructure has been built in the name of modernisation, progress and development, the impact on the region is diverse and even paradoxical, including on tourism. The aim of the research is to examine the role of road infrastructure in tourism development, in two directions: (1) infrastructure and its associated content as a tourism offer; (2) infrastructure as a

[1] The research presented in this paper was conducted as part of dissertation research and is contained in the unpublished dissertation Jarec, Morana. 2021. "Infrastructural projects and socio-cultural construction of space in Gorski kotar" („Infrastrukturni projekti i društveno-kulturno oblikovanje prostora u Gorskome kotaru"). PhD diss., University of Zagreb. https://doi.org/10.17234/diss.2021.8597. Part of this research was also presented at the 23rd Congress of the European Anthropological Association „Anthropology in the Anthropocene: Exploring Human Influences on the Global Ecosystem" in Zagreb, Croatia, 5-8 September 2024.

facilitator or obstacle to tourism development; as seen by the local population and its users.

Gorski Kotar is a rural region in western Croatia, bordering Slovenia to the north and north-west, the Rijeka coast to the south-west, and region of Lika to the south-east. It is part of the Primorje-Gorski Kotar County. For a long time, the region was characterised as an isolated area, but since the first half of the 18th century and especially in the 19th century, with the construction of roads and the exploitation of forests, the importance of Gorski Kotar as a transport and trade centre between the coast and the Croatian mainland has steadily increased. Gorski Kotar is very different in appearance from the surrounding regions: it has a high mountain character, although its peaks are slightly higher than 1,500 metres, with extensive forests. The settlements are scattered, with no significant concentration of population. It covers an area of 1,270 km2, two thirds of which is forested (Lukić et al., 2009: 158). There are three towns (Čabar, Delnice, Vrbovsko) and six municipalities (Brod Moravice, Fužine, Lokve, Mrkopalj, Ravna Gora, Skrad) with a total of 18,954 inhabitants, which corresponds to a density of only 15 inhabitants per square kilometre (The Croatian Bureau of Statistics, 2021).

Gorski Kotar is an area that, by land, offers the only possibility of connecting the interior of Croatia - and thus Central Europe - and the northern Adriatic coast. The construction of the first macadam roads through Gorski Kotar breathed new life into the settlements they passed through and touched, accelerated the development of Gorski Kotar, their routes changed and modernised over time and are still of great importance to the lives of the inhabitants today. The Lujzijana Road was the first modern macadam road to pass through Gorski Kotar. It was built between 1803 and 1811 and connected the towns of Rijeka and Karlovac.[2] It was of great importance for the development of the region: it led to an increase in the number of inhabitants and immigration to the settlements along the route, new professions related to the road emerged, such as blacksmiths, farriers, innkeepers, etc., social life developed, many associations were founded, as well as schools (Jarec, 2021). The material features of the Lujzijana Road such as bridges, retaining walls, milestones and cisterns are considered “elegantly and architecturally unusually designed” (Szavits Nossan, 1970: 188). Early travellers described the Lujzijana Road as “the fruit of many years of experience and a rich spirit of invention” (ONB, 1805: 57), that deserves “admiration” (ibid.: 58) and as “one of the most beautiful roads” (ANNO, 1830: 43). The modernity of the road infrastructure also attracted postcard producers who recognised the potential profit from this novelty, a modern spectacle. Stories about the construction of the road and its builders, unusual and famous travellers, vehicles and cargoes, anecdotes, information about the service in the taverns and inns, the interaction between travellers and locals, and generally about the way of life represent the intangible elements of the Lujzijana Road.

Even though it has been rerouted and modernised over time, the Lujzijana Road is of such great importance to the region that it is considered a landmark and cultural heritage. The road brought prosperity to the region as it facilitated trade and encouraged the development of transit tourism along its route. At the beginning of the 19th century, taverns and inns with barns were built out of necessity. Going to the coast or to the mainland, both travellers and animals had to rest from the journey. Later, other forms of tourism emerged, such as medical and sports tourism, with Gorski Kotar being a destination. At the beginning of the 20th century, more representative tourist and gastronomic facilities were opened, municipal infrastructure was developed and tourist activities were better organised (Knežević & Grbac Žiković, 2013: 118). Inns and restaurants were built for profit, and such establishments sprang up along the road. In the 1960s, with the development of summer resorts on the coast and increasment of the car

[2] First road connection between Rijeka and Karlovac was Karolina Road, built in the first half of the 18th century. However, with its frequent steep ascents and sharp bends, it did not served all the needs of trade and transit. In the second half of the 18th century, the need for a new road arose. This is the reason why Lujzijana Road is called the first modern macadam road in Gorski Kotar.

traffic on Lujzijana Road, transit tourism became one of the pillars of the Gorski Kotar economy (ibid.: 119-120).

The construction of the Rijeka–Zagreb motorway through Gorski Kotar in the second half of the 20th century marked a time of new changes in both physical and social space, in the lives of the local population and road users. The main function of the motorway is to direct economic traffic, especially tourist traffic, from Central Europe and the Croatian mainland towards the northern Adriatic coast and Istria, areas that are most visited by tourists. The construction of the motorway, which began in 1970 and was completed in 2008, had a significant impact on the further development of the region, including tourism. Tourists preferred to use the motorway to get to the sea faster, the journey was much shorter and it was no longer necessary to stop. With the opening of the motorway through Gorski kotar for traffic, transit tourism has lost its economic importance for the region. On the other hand, it relieved the traffic on the Lujzijana Road that runs through the settlements. The motorway was built through an already heavily depopulated region[3], and it contributed to the further emigration of the population of Gorski Kotar (Feletar, 2016: 225). With the decline in tourist traffic and the closure of businesses offering catering and gastronomic services, people lost their source of income and many of them emigrated to other parts of Croatia or abroad. Even though Lujzijana Road has lost its traffic importance, it is still used for local and transit transport. This includes users who do not want to pay motorway tolls, who want to get to know the region's countryside and towns, who want to avoid traffic jams and in the event of motorway closures (Feletar, 2016: 226).

Throughout history, the hospitality industry in Gorski Kotar has been conditioned by the development of roads through the region. In addition to its distinct transit importance and its natural beauty, the tourist potential of Gorski Kotar is also reflected in its proximity to the sea. While tourism is emphasised in the literature as the most important activity for the future, "requiring coordinated spatial solutions" (Wenzler, 1981: 263), in 2019 Gorski Kotar received a total of 40,506 tourist arrivals and 98,964 overnight stays were achieved, while in the entire Primorje-Gorski Kotar County in the same year a total of 2,966,489 tourist arrivals and 15,314,671 overnight stays were achieved (The Croatian Bureau of Statistics, 2019). This means that only 1.36% of arrivals and 0.05% of overnight stays are attributable to Gorski Kotar. In 2018, tourism and tourist activities accounted for only 2.8% of the total income of entrepreneurs in Gorski Kotar (Horwath HTL, 2020: 15).

Despite having adequate road infrastructure, the region struggles to attract tourists, who usually use the motorway to bypass Gorski Kotar on their way to the seaside. While "sun and sea" tourism dominates in the coastal areas, Gorski Kotar offers a different kind of experience, centred on cultural and historical heritage, nature and sports. However, this diversity is not adequately promoted or supported, partly due to insufficient investment by the state in tourism development. In 2021, none of the nine projects applied to a call for proposals *Investing in starting, improving or expanding local basic services for the rural population, including recreational and cultural activities and related infrastructure* (Krmpotić, 2021). The same scenario repeated itself in 2024, when six tourism projects from Gorski Kotar submitted to the call for proposals for the *Croatian National Resilience and Recovery Plan* did not make it into the selection of eighteen projects that are 100% co-financed by the EU and the state (Bičak, 2024). All projects from Gorski Kotar, which have a combined

[3] Gorski Kotar reached its demographic peak in 1890 when it had 43,518 residents. In 1961, it had 38,088 residents, but major declines happened between 1971 and 1981 (in 1981 it was registered 31,692), and between 1991 and 2001 (in 2001 it was registered 26,120 residents) (The Croatian Bureau of Statistics, 2001). In 2011 census it was registered 23,011, and in 2021 only 18,954 residents (The Croatian Bureau of Statistics, 2011; 2021). In the mid-20th century, there was a significant shift in the population of Gorski Kotar towards non-agricultural activities, however there was not an urban regional centre that could provide employment opportunities. In addition, growing influence of cities outside the region (Zagreb, Rijeka, and Karlovac) has gradually led to the depopulation of smaller settlements (Feletar, 2016: 209).

value of 25 million euros, ended up on the so-called reserve list (ibid.).

Adding to these challenges, the region has experienced significant depopulation throughout history, resulting in a high proportion of elderly and retired residents (Lajić & Klempić Bogadi, 2010; Lajić, 1999). This demographic shift has weakened the local social capacity to advocate for projects or independently initiate large-scale development efforts. Nevertheless, the enthusiasm, ambition, and positive attitudes of the local population towards developing tourism remain evident. The establishment of the Gorski Kotar Tourist Board in 2020 marked an improvement in the region's organizational structure, and local governments are beginning to take a more active role in tourism development. Despite this progress, the region still lacks sufficient recognition and support from the state. This underscores the need for greater collaboration between local and national authorities to unlock the region's full tourism potential.

Theoretical framework, methodology and literature overview

The road infrastructure is of great importance for this Croatian transit corridor and the roads are deeply rooted in the identity of its inhabitants, as they unite their human, spatial, economic and ethnographic situation: "All interests related to paths, roads and modern transport routes complete the picture of the personality of Gorski Kotar and can serve for ethnographic conclusions" (Gotthardi-Pavlovsky, 1981: 361). However, infrastructure in general is sometimes taken for granted, it is simply there, it exists. We do not think about where electricity comes from, how electronic messages travel across the planet, or where the water from the toilet goes. One of the first publications to address the methodological issues of infrastructure research is "Ethnography of Infrastructure", which argues that infrastructure is by definition "invisible" and that we only notice it when it fails, that is, only then does it become "visible" (Star, 1999: 380, 382). However, the "invisibility" of infrastructure is only one aspect of the whole spectrum. For the people who build it, live near it or depend on it, infrastructure is certainly very visible (Hetherington & Campbell, 2014; Kincanon, 2019; Masquelier, 2002). Infrastructure changes the world in complex, sometimes subtle, but also powerful ways. Its construction is inextricably linked to promises (Anand et al., 2018; Löfgren, 2004), and through it, citizens learn about the power of the state (Harvey & Knox, 2015). Although infrastructure projects are conceived as projects of modernisation or progress, they sometimes pose challenges and threats, fail to fulfil promises, perceptions and expectations, and create inequalities. Their significance is therefore complex and their impacts are manifold. Regardless of whether it is political, economic or social power embedded in infrastructure, it has different effects in different places, at different times and on different people (Jarec 2021). Examining the importance of infrastructure for the local population and focusing on tourism development, this paper argues that infrastructure plays a complex and often overlooked role in shaping spaces and that it can favour both progress and underdevelopment.

This research examines how individuals in local communities perceive role of road infrastructure in tourism development as a cultural and social phenomenon. Tourism inherently involves the movement of people, cultural exchange, and the transformation of local spaces, it shapes cultural representations and power dynamics. It impacts local economies, identities, and social structures and reflects broader global-local interactions. Exploring local perspectives contributes to understanding how tourism trends intersect with rural areas and local ways of life. The first part of the results and discussion is dedicated to the Lujzijana Road, which is considered a cultural heritage by the local population. Their perspectives, experiences and efforts are presented to illustrate the desire to turn it into a tourist product in the form of a cultural route. Even though they have not been successful, some road users choose to travel and sightsee along Lujzijana Road, whether for nostalgic reasons or out of a desire not to rush anywhere. The second part of the results and discussion focuses on the Rijeka–Zagreb motorway. Even though it led to the closure of local businesses that profited from transit tourists, it was built out of necessity, as the amount of

traffic flowing through Gorski Kotar could not be managed on the Lujzijana Road. This article is not a plea against the motorway, but examines the promises and predictions about the impact of the motorway on the region, especially on the tourism sector, as well as opportunities for mutual benefit, through perspectives of the company managing the motorway and local community. As this research seeks to understand local perspectives and lived experiences, the methodology used includes qualitative methods, key tools of anthropology: desk research, observation with participation, and semi-structured interviews conducted in the period from 2015 to 2020. Participation in the tour for local enthusiasts and entrepreneurs was arranged by the Lujzijana Association and provided an opportunity to have informal conversations about the challenges and opportunities in tourism sector. Some of the interviewees were found through the same association, others through the snowball method. Men predominated among the participants, and the average age was 60. All participants quoted in the paper are identified by their age.

The Rijeka–Zagreb motorway's negative effect on the region was examined by the geographers Aleksandar Lukić, Vuk Tvrtko Opačić, and Ivan Zupanc (2009). The paper highlights that the opening of the motorway has exacerbated regional disparities, leading to economic regression in areas along the Lujzijana Road while benefiting settlements near motorway intersections. Main methods include analyses of demographic statistics, traffic information, and technical data related to the motorway, and field research involving mapping, questionnaires, and interviews in catering units along the Lujzijana Road, as well as in households in two settlements in Gorski Kotar, one that found itself in a disadvantaged position with the opening of the motorway, and the other that prospered economically after the building of the new motorway intersection. Art historian and museologist Klementina Batina (2004) discusses the heritage of Gorski Kotar, emphasizing its rich material and immaterial cultural identity that remains underappreciated. The paper identifies various natural and cultural attractions that can enhance tourism in Gorski Kotar, while also addressing the need for improved infrastructure and accommodation. Ethnologist Tihomira Stepinac Fabijanić (2016) published a paper about traditional culture along the Lujzijana Road, focusing on the Gorski kotar. She discusses the impact of the road on local architecture, folk costumes, and traditional crafts, highlighting their evolution from the 19th century to the present. The research incorporates bibliographical data and ethnological notes from field studies, emphasizing the significance of preserving cultural heritage amidst modern influences. It also addresses the socio-economic changes in the region due to migration and the decline of traditional practices. By investigating the economic significance of transit tourism in Gorski kotar, Rade Knežević and Renata Grbac Žiković (2013) highlighted its evolution through four distinct periods. The paper emphasizes the need for revitalization strategies in areas where transit tourism has diminished, highlighting the complex socio-economic implications of these changes.

While previous studies have analyzed the economic, demographic, and cultural impacts of road infrastructure in Gorski Kotar, there is a certain gap in representation of local residents' perspectives and how they engage with these roads as part of their everyday lives. By conducting fieldwork several years after the motorway's completion, this research provides novel insights and evolving attitudes towards these infrastructures. It bridges the gap between ethnographic and infrastructural studies by examining not only the practical functions of these roads but also their symbolic and cultural significance (see also Jarec, 2019).

Results and disscusion

With its architectural and monumental values, its history and significance, and the nature that surrounds it, Lujzijana Road represents an untapped tourist treasure. Although the development of transit tourism in the second half of 20th century has given the area around Lujzijana Road the physionomy of a tourist region and despite the large tourist traffic, the area around the road has not become a functional region: non-commercial facilities such as car parks and their equipment (marked parking spaces, sanitary facilities,

playgrounds, outdoor tables and benches) as well as more complex accompanying facilities such as information centres have not been built along the road route (Knežević & Grbac Žiković, 2013: 124). However, the Lujzijana Road, with its tangible and intangible components, is increasingly being recognised as a cultural heritage and historical attraction that has the potential to become a valuable tourist product in the form of a rural cultural route (Perinić Lewis & Jarec 2016). It would serve as both a tourist destination and a tourist transit product. In the search for new tourist attractions and new tourist products, modern tourism is increasingly turning to cultural routes, specially established tourist paths or roads along which thematically orientated tourists move (Kušen, 2013: 37). A cultural route, according to the definition of the authors of the Manual for the Management of Tourist Visits on Thematic Cultural Routes, is "a physically tangible section in space defined by an inventory of tangible and intangible, cultural and historical elements that are linked thematically, conceptually or by definition, as well as by the identification of locations of existing cultural assets that are linked in a punctual, linear or regional structure; that form a marked and interpreted continuous whole within the unique context of the route" (Androić et al., 2012: 7). The non-governmental organisation Lujzijana played a central role in the attempt to turn the Lujzijana Road into a cultural route. It commissioned the Croatian Institute for Tourism to carry out a tourist evaluation of Lujzijana Road. The Institute published a study entitled *Lujzijana as a Cultural and Historical Attraction: A Development Concept (Lujzijana kao kulturno-povijesna atrakcija: razvojni koncept)*, whose authors recognise that "the evaluation of this road and the wider area through which it passes can serve for a better market positioning of Gorski Kotar and for a more systematic organisation of the offer in this micro-region, with the aim of generating more tourist traffic that would promote medium and small tourism entrepreneurship, create new jobs, reduce the sense of isolation of the inhabitants of Gorski Kotar and affirm their cultural identity" (Kušen & Tomljenović, 2009: 68-69). This study analyses the tangible components of the Lujzijana Road as potential and real attractions, such as architectural landmarks, service and catering facilities, milestones, bridges, cisterns, tree-lined avenues, viewpoints, etc.; also lakes, caves, forest parks, castles and settlements as rural attractions, and states that the attractiveness of the Lujzijana Road also includes its intangible cultural-historical segment (ibid.: 70-78), such as the manner of its construction, its builders, historical stories related to the construction and use of the road, and the way of life. Although the authors emphasise that some of the material components need to be renovated and accommodation capacities adapted, and that the counties need to make numerous creative and financial efforts, they predict that by 2012 the Lujzijana Road will be "the first fully integrated cultural and tourist route; the Lujzijana Road will be a recognisable tourist product of Croatia, basing its recognition on a well-organised cultural and tourist offer, a professional itinerary management system and quality tourist services" (ibid.: 81). However, the local governments were not interested in developing this project any further. In 2014, the Lujzijana Association entered into cooperation with the Institute for Anthropological Research, the Archaeological Museum in Zagreb and the Municipality of Kočevje in Slovenia to apply for funding from the Instrument for Pre-Accession Assistance (IPA) for cross-border cooperation between Croatia and Slovenia with the project *Historical Roads and Trails of Gorski Kotar and the Kočevje Region*. The following year, after becoming the Lujzijana Cooperative, they drafted a project entitled *Historical Roads and Trails of Gorski Kotar – Cultural Routes* with the intention of obtaining funding from the European Agricultural Fund for Rural Development (EAFRD), with the possibility of including the Lujzijana Road in international cultural routes. These activities are some of the examples of the efforts and interest of the local population to improve tourism in the region with their own efforts. The President of the Lujzijana Cooperative said:

Our goal is to attract as many owners of family farms, as many tourist sites and everyone else who has something to do with the tradition of the historic roads of Gorski Kotar, and to give them not only the opportunity to enter the network of these historic roads, but also to have the opportunity to apply for EU funds through this project, which can

improve their offer, and that means creating the basis for increased revenue. Unlike some local governments and tourist boards in Gorski Kotar, that have shown no interest so far, the entrepreneurs, craftsmen and owners of family businesses in this area understand what an opportunity this is for their development, so they are cooperating to a very high degree and I can say that the response is so great that we have to choose. (Androić according to Krmpotić, 2015)

Although the above projects have not been accepted for funding, they show that the driving forces for activities to enhance tourism, revitalise and economically recover the region are the local population, local associations, individuals, small entrepreneurs, family business owners, etc., while local governments and tourist boards "still show no interest". In the Master Plan for the Tourism Development in Gorski Kotar, the Lujzijana Road is not mentioned at all (Horwath HTL, 2020). In conversations with the locals, we learn that they feel forgotten and are dissatisfied with the authorities.

Firstly, we don't have tourist agencies, secondly, at a national level, not everyone in the tourism sector sees us as someone special to invest in... (Thirty-year-old woman)

Our tourism office here only has one employee and one volunteer. And if there's no that intern, then there is only one person. I don't know how you think, but one person for the tourist office... I think that's impossible. (Sixty-year-old woman)

The Lujzijana Cooperative organised numerous other activities, public forums and meetings to raise funds for its efforts and put ideas into practise. It was also the organiser of the tourist tour of Lujzijana Road in 2015, which was an opportunity for fieldwork for this research, observation and participation. On that occasion, one of the organisers said:

We are witnessing this terrible depopulation process in Gorski Kotar. Everyone who is familiar with these demographic trends knows that one of the elements is the loss of territorial identity or the loss of the sense of belonging of the local population, with the economy of course being the most important part. When we talk about the economy, I will tell you a terrible fact that nobody really emphasises, probably to hide the incompetence of the people who should be developing tourism. Primorje-Gorski Kotar County has a share of about 20% of the total tourism product. In terms of overnight stays and the number of arrivals, it is in second place, just behind Istria County. Twenty per cent in Croatia! Even ahead of Dubrovnik! And that Gorski Kotar accounts for less than 0.5% of this product, in this heritage that we are talking about now, despite the national park, protected nature, natural beauties and, most importantly, the transit corridor… You have to drive through it, it connects Central Europe with the northern Adriatic ports! (Fifty-year-old man)

The former president of the Rijeka Road Association was one of the speakers at the tour of Lujzijana Road who spoke about his own efforts to preserve the architectural heritage of Lujzijana Road:

I tried, that was the article we wrote, in 2008 we went down Lujzijana Road and tried to give some guidelines on what should be done to preserve it. In 2008, we laid out everything that should be done, of which only the sundial was renovated and nothing else. And we passed on the conclusions from that trip to everyone, from the Ministry of Culture to Croatian roads, Croatian motorways, tourist boards, I don't know, Rijeka, Čavle and everyone else along the Lujzijana Road. (...) We edited it and sent it to all these addresses, and we got nothing, not a single reply, not even criticism from anyone. (Sixty-year-old man A)

In addition to the aforementioned sundial, which was renovated on the initiative of the Rijeka Road Association, one of the milestones on Lujzijana Road was also renovated by Croatian Roads and the Municipality of Čavle. It is located within the serpentine, where a rest area has also been set up so that one can stop at the viewpoint. In addition to its tourist function, the restoration of these historical structures and features is also a way of protecting and safeguarding social memory. In order to make the journey a tourist experience, architect Kušen also emphasises the need for a long-term strategic goal of equipping state roads with an appropriate number of rest areas, viewpoints and accompanying service facilities that can be used to promote the area through which the road passes, but also the entire Croatian tourist offer (2013: 35).

Travelling along the Lujzijana Road as a tourist road or unofficial cultural route has nevertheless taken place. The publication of the book *On Old Roads to the Sea (Starim cestama do mora)* by Lara Černicki and Stašo Forenbaher in 2012 marked a turning point in the tourist experience of the Lujzijana Road. It offers a systematic overview of the history and characteristics of four roads, written in the style of a travelogue. The book's foreword states:

We have travelled the old roads countless times, since the time when they were the only roads on which one could travel to the coastal towns. For us, they were just a means to get to our desired destination. Many years later, after the initial enthusiasm for the new motorways, we realised that although we were saving time by rushing, we were losing the very essence of travelling. So, we started travelling the historic roads again, sometimes by car, sometimes by bike and sometimes on foot. We visited them step by step, hoping to find any trace that might tell us something about their past. There is not much traffic on the old roads. You can drive along them at your leisure and enjoy the landscapes, the architectural skill and the sense of beauty left behind by their builders. You will have the opportunity to discover hidden corners and neglected traces of the past. Perhaps you will at least briefly feel the spirit of the old days, when people still travelled by carriages and ox carts. Distance, speed and time had a completely different, now forgotten meaning. (Černicki & Forenbaher 2012: 8-9)

The authors are actually writing about deceleration. Slowing down today means reducing the speed of an ever-growing regime that is built on the logic of speed (Vannini, 2014: 116). For Phillip Vannini, who deals with the sociology of everyday life, slowing down therefore means influencing the way we inhabit the world and in turn be influenced by it; slowing down means behaving and moving differently, experiencing the environment in a way that is counter to the logic of speed; slowing down means conceptualising life differently, imagining time as an alternative to the logic of speed – for oneself and for others (2014: 117). Vannini builds his argument of slowing down - of travellers, tourists and things that move "slowly" - on tactics (de Certeau, 1984), as oppositional everyday practises, that is, as opposites to the dominant culture of speed. Examples of deceleration include the slow preparation of food, so-called Robinson tourism, a way of life without electricity, etc. Tourists interested in such slow tourism and slow travel are interested in locality, ecology and quality of life, which has its roots in societal pressures for lower-carbon travel and less commodified tourist experiences (Dickinson & Lumsdon, 2010: 1). Slowing down is also a way of increasing physical skills to develop a reflective awareness of self, movement and sense of place (Vannini, 2014: 122-123). From conversations with road users through Gorski Kotar, it appears that efforts to promote

such slow tourism are also justified from the tourists' perspective:

Someone who organises tourism in Primorje-Gorski Kotar county, (...), would have to somehow get tourists to turn off the main road to see something, you have to offer them something. So, you have to see a building, a natural beauty, and you have to offer them something to eat. And then maybe you can entice them to get out of the car. But it's obvious that more and more of these tourists who are travelling by car are doing exactly that, exploring the area, driving on local roads, seeing the local population, seeing the beauty of nature, more and more people are functioning in that way. We do that too. And Gorski Kotar could do a good job here, because it has all the prerequisites for interest in such a trip. In my opinion. And good food and beautiful nature and strange landscapes, and the climate. The summers are colder, in winter there's a real winter atmosphere. (Sixty-year-old man B)

For many interested travellers, the book *On Old Roads to the Sea* served as a travel guide or handbook. Some of those who picked up the book travelled and documented their journey themselves with descriptions and photographs on social media. Those online travel writers, follow the book's instructions and literally copy parts of the book into their texts. They want to inform readers about historical features, write down their impressions, discover new places, they photograph milestones, bridges, dilapidated inns and look back nostalgically on ancient times: “there was also a rest house for tired travellers; today it is difficult to see the former liveliness of people, horses and other animals; but there was eating, drinking, shouting, kissing, fighting; and then it was quiet” (*On Old Roads to the Sea*, Facebook page 2015); and also on the recent times, when the Lujzijana Road was the busiest: “we turn into Lujzijana, drive through Zdihovo[4] – a graveyard of once successful and always crowded restaurants, where the smell of spit roasted lamb spread for kilometres” (*Time on Two Wheels (Vrijeme na dva kotača*), blog 2019).

In 2009, geographers Lukić, Opačić and Zupanc also saw the possibility of transforming the Lujzijana Road into a cultural route and pointed out the problem of inadequate coordination and communication: “The activities that have already begun are not coordinated with the motorway construction project” (Lukić et al., 2009: 166-167). According to historian and geographer Petar Feletar, the modern Rijeka–Zagreb motorway, in conjunction with the natural and socio-geographical features of the wider area, has finally valorized the road connection from the Croatian interior to the coast (2016: 20), and the author of a monograph on the same motorway calls it the “road of life” (Moravček, 2007). In a broader, national and regional context, it is a modern material creation that has successfully overcome the mountainous obstacles of the region and, by enabling higher speeds, shortening the journey, has contributed to the overall economic development of Croatia, especially in terms of tourism. However, the complex significance of the Rijeka–Zagreb motorway for Gorski Kotar is palpable. Plans and predictions of a positive economic impact on the Gorski Kotar region can be traced in the literature from the time before the motorway was built. The monograph of Gorski Kotar from 1981 predicts an increase in the tourist value of the region through which the motorway passes, as well as industrial development: “Due to the proximity of the large urban centres of Rijeka, Zagreb and Karlovac, especially when the new

[4] Zdihovo is a settlement on the Lujzijana Road. It used to be a popular stopover on the way to the sea.

motorway is built, the tourist value of the Central Region[5] will increase considerably" (Pavić, 1981: 16):

Even today, the Central Region is of great importance in terms of transport, as the planned new four-lane Zagreb–Rijeka motorway is to be built here between the old Karolina[6] and Lujzijana roads. This motorway will not pass through settlements, but will have junctions and intersections with existing roads. This new road should stimulate industrial development in the Central Region. (ibid.: 15)

Others also wrote about the expectations that the Rijeka–Zagreb motorway will have a positive impact on tourism in Gorski Kotar due to the proximity of cultural-historical sites and to the motorway (Batina, 2004: 190; Androić, 2007; Kušen & Tomljenović, 2009: 69). The company managing the Rijeka–Zagreb motorway committed itself in its monograph to "cooperation with the community in the areas through which the road passes" (Prskalo according to Moravček, 2007: 11-12), and its website states:

The increasing transit through Gorski Kotar is of great importance because it connects the Croatian coastal area with the mainland, which also has an impact on the economic development of Gorski Kotar, especially tourism. This leads to an increase in employment opportunities for the local population in various economic sectors along the motorway. (ARZ, n.d.)

Although the monograph *Motorway Rijeka-Zagreb (Autocesta Rijeka-Zagreb)* from 2007 does not provide any information about the manner of co-operation with the local population, it continues:

When planning the Rijeka–Zagreb motorway, special attention was paid to harmonising the route with the landscape qualities, so that the construction of the motorway, including roadside service facilities as its components, preserves the authentic indigenous values of the natural and anthropogenic landscape, such as the natural relief, the richness and integrity of biocenoses, individual biotopes and the totality of biotopes, existing settlements, nature reserves and more. (Moravček, 2007: 294)

Other studies proved that the motorway actually showed social insensitivity towards the local community: limited employment opportunities in the service facilities along the motorway, the inability to promote rural households and restaurants that already existed on Lujzijana Road and elsewhere, the lack of signposting to landmarks and natural phenomena (with the exception of Risnjak National Park) or the possibility of using Lujzijana Road as an alternative route (Lukić et al., 2009: 16), all of which is actually understandable from the point of view of the company managing the motorway and collecting the toll.

What the company benefits from directly, however, are the service areas along the motorway, which could be designed in such a way that they also benefit local tourism. The Rijeka–Zagreb motorway in the Gorski Kotar region has two rest areas: Kupjak, which can be approached from both directions, and Lepenica, with access from the direction of Zagreb. Both are designed with no particular regard for region-specific values. There are several publications by architect Eduard Kušen (1999, 2013) on motorway service areas and how they should look and function, how they

[5] According to the geopolitician Radovan Pavić, the Central Region is a part of Gorski Kotar that extends through the central part of Gorski Kotar, between Bosiljevo and Severin in the east and Gornje Jelenje in the west, its other borders consist of higher mountain relief, which begins in the west at Crni Lug and in the southeast at Mrkopalj and Ravna Gora (Pavić, 1981: 14).

[6] See footnote 2.

should be arranged, organised and equipped, and how they should relate to the passenger experience: motorways and their rest areas are the first points of contact for travellers and tourists, especially from abroad, providing the first impression of the region and country they are passing through. A motorway rest area should be protected from wind, noise, smells and polluted air, be outside the “stress” zone, have adequate vegetation and forest cover, have viewpoints and be close to historical sites and buildings, contain children’s playgrounds, picnic areas, benches and information boards – these are what Kušen calls “humane” features (Kušen, 1999: 16). In addition to the above-mentioned contents, the rest areas should also have regional characteristics in their appearance. For modern tourism, it is no longer enough for motorway rest areas to be clean and well-maintained, they must also be recognisable and attractive to tourists and thus contribute to the quality of the traveller's tourist experience: “In addition to the utilitarian aspect, which is essential for users, and the support of road safety, it is necessary to provide relaxation and comfort for passengers of different age groups and to unobtrusively interest them in the values of the space and regions they are passing through by introducing them to the cultural, historical, natural, gastronomic and other attractions of the immediate and wider surroundings” (Mlinarić according to Kušen, 2013: 21). Kušen is of the opinion that Croatia missed the opportunity in the 1970s with the construction of new motorways to “optimally valorise rest areas along its most important road routes for tourism: these rest areas as a central framework for all accompanying service facilities are usually callously located, programmed and designed, exclusively according to engineering standards of minimum distances between accompanying service facilities, and are located on inhumanly elongated construction sites in the stress zone along the road” (Kušen, 2013: 23). *The Master Plan for the Tourist Development of Gorski Kotar* (Horwath HTL, 2020: 92-93) proposes the establishment of a tourist information centre for visitors to Gorski Kotar as a tourist infrastructure to be located in the existing Kupjak service area, a large roadside service area that already contains a petrol station, restaurant, children's playground, car park and other facilities. The aim of the project is to create a unique place of information about the tourist offer of Gorski Kotar, where motifs and experiences of Gorski Kotar as well as local products, gastronomic specialities and activities in the destination will be presented (ibid.). The centre should also be interactive and technologically equipped (virtual reality, touch screens, etc.) and have an outdoor area that would attract guests in transit (ibid.). However, the steps that need to be taken are challenging, such as determining a micro-location on the existing service area, defining an architectural solution, securing funding, building the centre, to name but a few, and bearers of the projects should be Gorski kotar Tourist Board and the Municipality of Ravna Gora, according to the proposal (ibid.). The authors of the plan have not estimated the level of investment as it depends on a number of factors. The proposed project highlights a promising vision of a centre that could serve as a gateway to the region, showcasing Gorski Kotar's unique attractions and creating stronger connections between transit travelers and the local community. Significant challenges remain, including securing funding, so the project has not yet been realised.

In the monograph of Gorski Kotar from 1981, the same author who predicts economic growth through the motorway also sees a different future. Due to Zagreb's aspiration for the sea as the most important emitting focal point in Croatia, Gorski Kotar retains only a small number of guests passing through it (Pavić, 1981: 16), and also:

The advantages of the geographical location of the Central Region are mainly related to its use as a transit route since the beginning of the 18th century, which benefited the economic development of Gorski Kotar – although the location of the passage, in addition to the possibility of integration into the economic life of other regions, can also become a cause of its own backwardness, because the main forces of economic development do not have to affect the transit area. (Pavić, 1981: 15)

Although it improves access to the larger urban centres, the rural area through which the motorway passes falls into a "communication shadow" (Lukić et al., 2009: 156), or assumes a tunnel effect (Graham & Marvin, 1996: 60). The tunnel effect is caused by the uneven "bending" of temporal and spatial barriers by an advanced infrastructure network that aims to bring urban environments into interaction while excluding most of the space through which it runs (ibid.). It is not only motorways that have the tunnel effect, but also air and rail transport and other types of infrastructure created in the search for greater speed (Andreu according to Graham and Marvin, 2001: 202). Participants in this study confirm that the Rijeka–Zagreb motorway has not brought any good to Gorski Kotar, but has caused the decline of many catering establishments and a decrease in tourist visits.

That's a minus for Gorski Kotar, because they said it would be a plus, it isn't... Nobody sees you, you zoom off to Rijeka and see neither Ravna Gora nor us (Brod Moravice), and again we are nowhere. (Sixty-year-old man C)

I mean, we're dying a little, that's not new. I'm afraid we've reached the end of the road. A very important reason for this is that a modern road, a motorway, has been built near Ravna Gora, which has taken over the traffic. People used to come to Skrad and park in the big car park down there or the slightly smaller one up there, they would park their car and go to the bar that was open back then. And then they would have a bite to eat there, then they would have a drink, and then they would interact, you know. The people from Zagreb used to say: 'We' ll have lamb in Mirni Kut, we'll have cottage cheese with cream in Skrad and in Lokve...' there's nothing left there now, there are just the remains of the power station by the road, I think there used to be a big restaurant there, you know. Now there's nothing left, everything is as if nothing ever happened there. There's nothing there anymore, only the power station is still there. And then they would drove through Jelenje on this winding road down to the main road and then to Crikvenica, or to Krk. (Eighty-year-old man A)

It did no good. It bypassed... Listen, along Lujzijana the lambs were turning, it was all full, even towards Moravice, it's all gone now. There were famous restaurants there. And now they are operating at a lower capacity or have simply disappeared from the map. Because all that took place in these small communities, in these inns and pubs, tourism retained here. And now, listen, the bus lines have disappeared… For example, Skrad, you just have to work hard, you have to have an idea, then you can turn it to your advantage. Skrad has completely deteriorated. In the sixties it was a tourist place, you had bus stops, fifty buses stopped there every day. They stopped there for half an hour, and you could get coffee, strudel, gemišt. If one doesn't have a car now... I don't know how many lines there are, if you can catch one or two to Zagreb. The one who doesn't have a car… it is a bit of a problem. (Sixty-year-old man D)

The motorway is different, when the motorway came, everything died. And when the old road was, oh my, in Skrad there was... a hotel, a bus station, there was... everybody stopped and it was like a rest area. Until this road took over traffic. It was

trendy to go to Skrad, to party and so on. And the express trains stopped there, they wouldn't stop at every station. Fast trains stopped in Skrad. Tourism ruled in Skrad. (Eighty-year-old man B)

On the other hand, communities and especially entrepreneurs near motorway intersections do not share the same experience. Motorway intersections determine development through their location. They are few in number but they have clear advantages: they are the access and connection points, and enable the dispersion of traffic flows into the surrounding area (Sić 1997: 86). The Rijeka–Zagreb motorway has four interchanges in the Gorski Kotar region, and their location has created new regional differences (Lukić et al., 2009). Some of the Gorski Kotar population surveyed believe that the motorway is beneficial for the tourist activities nearby motorway junctions:

There was a big camp in Lokve, the lake was always full of swimmers, a lot of, say, twenty or so boats, people were building boats there, fishing boats, Lokve was the centre of events, of tourism. What was good for Fužine is that they are now much better connected to the motorway than Lokve, it's not exactly direct, but it's somehow different. (Seventy-year-old woman)

(Motorway) doesn't bother us. It doesn't bother Kupjak. But it bothers them down there. It bothers Skrad, Severin and even Lokve. It's even better for us. I don't know... We have an exit from the motorway nearby... It's great for us. (Seventy-year-old man)

With what we do, if I had to tell a man from Zagreb that it would take him two and a half hours on the old road, he would give up. I tell him you'll be here in 50 minutes. (Thirty-year-old woman)

The great advantage of this part of Gorski Kotar is that when lazy people from Primorje get in the car, they get here in 12 minutes from Grobnik. Believe me, they would black out if they had to drive two minutes longer. (Forty-year-old man)

Communities located near motorway interchanges have experienced some positive changes, benefiting from better accessibility and increased regional traffic. These areas have capitalized on their proximity to the motorway and have seen improved connectivity for tourists and businesses alike. This divergence in experiences adds to the complex, uneven impact of the motorway on Gorski Kotar.

Conclusion

The Lujzijana Road represents a significant yet underutilized cultural and historical asset with the potential to become a major tourist attraction. Despite rich architectural, historical, natural and symbolic features associated with Lujzijana Road, the lack of investment in basic and advanced tourist infrastructure has hindered its transformation into a functional tourist region. However, ongoing initiatives by NGOs and individuals demonstrate a strong local commitment to revitalizing the road as a cultural route. These efforts highlight the potential for leveraging EU funding and fostering collaboration among local stakeholders, including family businesses and rural entrepreneurs, to create sustainable tourism opportunities. While local associations, entrepreneurs, and community members are the driving forces behind initiatives to enhance tourism and preserve cultural heritage, a lack of support remains a significant obstacle.

By integrating the tangible and intangible heritage of the Lujzijana Road into a cohesive cultural tourism product, this initiative can contribute to economic growth, cultural preservation, and enhanced regional connectivity, ultimately positioning the road as a recognizable and valued element of Croatia’s tourism landscape. The

Lujzijana Road has organically developed into an unofficial cultural route, attracting tourists interested in slow travel and the rediscovery of historical paths. This deceleration aligns with modern trends in sustainable tourism. By addressing the gaps in coordination and leveraging the growing interest in slow tourism, Gorski Kotar could revitalize this historic route, fostering economic growth while preserving its unique identity. The shocking disparity in tourism contributions despite its strategic location and natural and cultural assets highlights the urgency of addressing these issues. By fostering collaboration between stakeholders and leveraging existing resources, there is an opportunity to transform the Lujzijana Road into a vibrant cultural route that also strengthens the sense of identity and belonging among its residents. The significant lack of funding and the fact that the government is not interested in developing tourism in Gorski Kotar leads to a feeling of isolation and helplessness among the local population, as well as the feeling that they have been forgotten by the institutions, a sense that they are not important.

Gorski Kotar already has a perfect means of getting to these attractions quickly: The Rijeka–Zagreb motorway. While it holds significant potential to positively impact tourism in Gorski Kotar, its actual implementation has fallen short of fully integrating the region's cultural, historical, and natural assets into the travel experience. The motorway has led to the decline of tourism in smaller, rural communities, particularly those that once thrived as rest stops along the old Lujzijana Road. Formerly bustling towns have seen a decrease in visitors, a reduction in local businesses, and a loss of traditional interactions that were central to the area's tourism culture.

The juxtaposition of the Lujzijana Road with the modern Rijeka–Zagreb motorway highlights the dual nature of development in the region. While the motorway has brought economic benefits through faster travel and enhanced connectivity, it has also overshadowed the historical significance of older routes like Lujzijana Road. The “tunnel effect” of the motorway have created a divide, with urban areas benefiting from the speed and accessibility of the road, while rural areas are left marginalized and disconnected. The lack of coordination between heritage preservation and infrastructural development, underscores missed opportunities for integrating these elements into a cohesive tourism strategy. Optimizing the motorway's potential requires a holistic approach that aligns infrastructure development with tourism strategies that prioritize local heritage and community benefits. By doing so, Gorski Kotar could transform its transit zones into meaningful destinations, leveraging the motorway to drive sustainable tourism growth and regional revitalization. To maximize the benefits of the motorway for the entire region, future efforts should address these disparities by promoting tourism and economic development in the less accessible areas, ensuring that the growth experienced by some does not come at the expense of others.

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IAR Publishing

Journal of Bioanthropology

Volume 4, 2024. p. 40-76

ISSN 2787-8201; UDK 572

https://doi.org/ 10.54062/jb.4.3.5

Developmental differences in dynamic indicators of three variously simple cognitive sub-systems functioning at girls and boys aged 8-17 years

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Received February 10th, 2025
Accepted for publication June 26th, 2025
Online First July 7th, 2025

Keywords: reaction time (RT), performance dynamics indicators (PDI), task complexity, cognitive development, sex differences.

Abstract

Mainstream post-Piaget cognitive development researchers mostly ignored performance dynamics behind the total paper-and-pencil tests score, or average reaction time (RT) on computerized tests. This research focuses on several indicators of performance dynamics while solving three simple computerized cognitive-motor tests of various complexity. To get developmental picture of the related cognitive subsystems dynamics, the tests were solved by girls (N=228) and boys (N=235) aged 8-17 years.

Participants were students of a primary and a secondary school from Zagreb (Croatia) that individually solved three simple tests of MID KOGTESTER-1 computerized reaction meter, which assessed predominantly perceptual and working memory functioning. Four RT dynamic indicators (minimal, maximal and average time of cognitive task solving, and average time of non-optimal cognitive task solving) were mostly positively correlated, sharing an average variance of 36% - thereby presenting non-redundant measures of cognitive dynamics. On a descriptive level, age-related decrement of all four indicators was non-linear, steadier for girls and suggested girl's superiority in the performance dynamics. The non-trivial and statistically significant results: (1) performance dynamics indicators improved across developmental phases with different intensities, the most in word recognition (WR) task and the least in choice reaction time (CRT) tasks, with the similar pattern for girls and boys; (2) across entire developmental period girls outperformed boys in WR and CRT task, but not in simple reaction time (SRT) task (the weakest advantage appeared in minimal time of cognitive task solving). Dynamics of cognitive subsystem functioning gives more complete picture of related cognitive performance and its development, based on neural structure and its dependence on age and sex.

Introduction

Fundamental cognitive development research, which is focused on the construction or evaluation of theoretical models of cognitive subsystems or human mind development, traditionally use validated instruments/tests of targeted cognitive constructs (Anderson et al, 2001; Demetriou and Kyriakides, 2006; Demetriou et al, 2013; Hicks and Bolen, 1996; Kail, 1997; McArdle et al, 2002). These instruments/tests usually report some total score in the test (whether it is paper-and-pencil or computerized test) or some average time of test item solving. This kind of report gives quite exact measure of person's average capacity to solve the tasks from the operative domain of the cognitive system under the study. Therefore, by looking these reports across months or ages of human developmental period, we will get an averaged picture of girls' and boys' joined capacity to solve the tasks in domain where the studied cognitive system operates.

However, could we get something more from the set of carefully chosen and validated cognitive tasks that are usually quite numerous (and demanding) with an aim to reliably assess the studied cognitive functions? Can we use the set of answered task outcomes – with and without errors – to get additional information (besides average capacity) on related cognitive system functioning? More precisely, can we assess: (1) how stable related cognitive system was while answering the tasks, or (2) what is its upper limit (i.e. best performance/potential) or (3) lower limit (the worst performance/operative weakness) during functioning?

This information are definitively useful in educational or vocational counseling of children and youth based on cognitive capacity (Gottfredson, 2003; Hodge, 1999; Metz and Jones, 2013; Wai et al, 2018), but can we use them to get more thorough insight in cognitive development dynamics in general? Can they tell when the cognitive system structure starts to change and when the change minimizes with a new harmonized and stable structure? Do stability indicators, or upper and lower performance limits, differ for girls and boys that maturate with somewhat different pace (Giedd et al, 2012; Lenroot et al, 2007; Thomas and French, 1985; Žebec et al, 2014)? Do performance indicators differ in simple and complex cognitive activities? Can they tell us how to design some long-term cognitive training or learning process based on a cognitive system under the study?

There are number of arguments from the other domains of cognitive psychology (fundamental or applied) that indirectly suggest positive or extended answers to these refined developmental questions.

Cognitive performance dynamics in non-developmental research

Intraindividual variability in human performance has been studied from perspective of various theoretical approaches and most of them concluded that it is not the consequence of cognitive system noise, but an inherent characteristic of the human that presents cognitive system stability (Boker and Nesselroade, 2002; Rabbitt et al, 2001; Slifkin and Newell, 1998). Stability of cognitive task performance (expressed via RT intraindividual variability) has been widely explored in processing speed-intelligence research (Deary, Der and Ford, 2001; Jensen, 2006; Neubauer et al, 1997). Theoretical models of an individual's RT distribution generated by performance in various cognitive-motor RT tests all include the σ or s parameter of intraindividual variability (Brown and Heathcote, 2005; Ratcliff and Smith, 2004; Ratcliff, Van Zandt, McKoon, 1999). Finally, the handbooks are written on human behavioral instability that cover various topics of this phenomenon: the role of intraindividual variability in cognitive-motor development, intraindividual variability and mood regulation and self-representation, interindividual variability as a measure of aging process and of vulnerability and resilience (Diehl et al, 2015).

When we move to the lower and upper limits of cognitive (sub)systems engaged in tasks solving, then we find intriguing research on worst and best RT task performance. The lower limit, i.e. worst RT performance in perceptual-motor RT test has been intensively studied under the topic known as *worst performance rule* (WPR). This rule states that during some cognitive-motor RT test solving, the longest RT correlates to intelligence scores more than average or minimal RT (Kranzler, 1992; Larson and Alderton, 1990; Schubert, 2019). This interesting finding actually says that the slowest responses in RT test tell us more about intelligence than the shortest one, or the average of all RTs, and possible explanation researchers looked at working memory (WM) functioning, especially in attention mechanisms of WM central executive (Coyle, 2003; Schmiedek et al, 2007; Unsworth et al, 2010).

The best (or the shortest) response time in cognitive-motor RT tests, although included in previously mentioned WPR research, showed its value predominantly in more applied studies. Because it presents someone's upper limit of RT-performance, it is quite sensitive to environmental conditions of the person engaged in RT test and her/his actual health status. Therefore, minimal RT indicator of performance dynamics various researchers used to analyze the impact of hyperbaric pressure and nitrogen narcosis in shallow air-diving (Petri, 2003), or to analyze the consequences of spontaneous menstrual cycle and of following oral contraceptives on cognitive motor

functioning (Becker et al, 1982). Moreover, minimal RT proved to be a useful indicator of kidney transplantation effects on cognitive and psychomotor functioning (Radić et al, 2011) and for difference analysis in complex psychomotor RT between patients with and without cerebral circulatory disorders signs (Bobić et al, 2002). Besides that, researchers used minimal RT to study RT sex differences at top sprinters (Lipps et al, 2011), but also in more fundamental research of mental processing dynamics (Drenovac, 2001, 2009).

Cognitive performance dynamics in developmental research

The answers on the above-mentioned refined developmental questions - on getting more thorough insight into cognitive development and related consequences from performance dynamics in the set of carefully chosen cognitive tasks - that come directly from cognitive development research, included mostly interindividual variability of performance, but only exceptionally it's lower and upper limits.

Intraindividual variability in cognitive development has been mostly studied within dynamic systems theory (DST) approach to cognitive development, where the authors defined it as a crucial mechanism of development (Smith and Thelen, 2003; Thelen and Smith, 1998; van Geert and van Dijk, 2002). Within this approach, the authors studied intraindividual variability in various developmental areas: in infant behavior (de Weerth et al, 1999), in manual reaching behavior during middle childhood (Golenia et al, 2017), in language development (van Dijk and van Geert, 2007), and many others.

Closely to DST, K. Fisher pointed to important role of intraindividual variability in his dynamic skill theory (Fischer and Yan, 2002; Yan and Fischer, 2002). Nevertheless, the other researchers of cognitive development also recognized the importance of intraindividual variability as a presumption of development and as a measure of cognitive functioning stability (Demetriou et al, 2013; Siegler, 1994).

Finally, intraindividual variability change across the lifespan was the research topic of authors interested in sex differences of this phenomenon (Deary and Der, 2005; Dykiert, 2012).

However, despite valuable findings of these developmental research of cognitive performance dynamics in answering the refined questions of the cognitive development, they did not include some useful dynamic indicators and methodological specificities of experimental cognitive research of reaction time (RT) in cognitive tasks. For example, these developmental researches mostly did not include upper and lower limits of cognitive performance that define the range of person's cognitive capacity (one rare exception was Žebec et al study, 2014). In addition, they did not differentiate cognitive from motor development in RT cognitive-motor tasks performance and although detangling cognitive from the motor component of RT response is an issue from embodied cognition perspective (Anderson, 2003; Wilson, 2002), there are models on how to do it, at least partially (e.g. Hick paradigm, described in Jensen, 2006, or in Neubauer, 1990). This differentiation is important because there are sources of specific motor variability that are a consequence of specific anthropometric features (e.g. hand dimensions, muscles development), minor somatic health confinements (e.g., ophthalmological, previous hand injuries), and previous experience in manual activities (e.g. related to computer games, specific sports). This motor variability confounds cognitive development assessment conducted by RT measures, designed in a way that demands manual actions. Finally, previous cognitive development research based on performance dynamics in cognitive-motor tests did not differentiate correct answers (to the test tasks) performed after errors, from correct answers performed after previous correct answer. This differentiation is important because errors in the previous RT task usually modify answering of the actual RT task while, depending on the subject's personality (e.g. emotional stability), they can prolong or even shorten RT answer of the actual task (Burns, 1971; Drenovac, 2009). In that case, we will not get a clear RT measure of targeted cognitive process.

In order to analyze cognitive development with as many indicators of cognitive-motor performance dynamics as we can derive it from an individual RT

distribution, by including motor and cognitive development differentiation and measures of targeted cognitive process decontaminated from errors impacts, we had to design developmental research with specific RT equipment. Moreover, to avoid confounding effects of girls' and boys' different developmental pace we included enough female and male participants and analyzed their performance in cognitive tasks separately.

Measures of cognitive development are numerous, but thorough insight in cognitive development asks for sensitive, real-time indicators that correspond to neurobiological bases of cognitive functions and, at the same time are noninvasive and applicable to larger groups of participants. Therefore, we used RT on cognitive-motor tasks that reveal the functioning of basic cognitive processes like perception and working memory (which contains attentional processes).

For describing performance dynamics of related cognitive sub-systems, we have chosen four indicators of performance dynamics in cognitive RT tasks that have been proved as valuable in the literature. Those were best (minimal RT), worst (maximal RT), and average time of cognitive task solving (mean RT), but also average time of non-optimal cognitive task solving (i.e. average non-optimal performance instability measured by mean deviation from best RT).

All previously discussed arguments directed this study toward empirically addressing several key issues. To check whether:

1. The four indicators of the cognitive component of simple cognitive-motor task solving separately contribute to the dynamics description of related cognitive sub-system functioning (i.e. whether they justify their inclusion in the description of activated cognitive sub-systems),

2. The four cognitive indicators of cognitive-motor task-solving dynamics improve across ages of the observed developmental period, and how possible improvement looks like,

3. Possible change of cognitive indicators of cognitive-motor task performance dynamics across developmental phases depends on (i) the dynamics indicator's type, (ii) cognitive task complexity, and (iii) person's sex (female/male),

4. There are sex differences in cognitive indicators of task performance dynamics and how they depend on (i) the dynamics indicator's type and (ii) cognitive task complexity.

Answering the above-mentioned problems should enable us to conclude whether the analysis of the cognitive component of cognitive-motor task-solving dynamics could give more complete and more correct picture of the cognitive development of perception and working memory systems and of cognitive functioning in general.

Materials and methods

Materials

The study included conducting three cognitive-psychological instruments, but only computerized reaction meter MID-KOGTESTER1 (Žebec, 2005; Žebec, Demetriou, Kotrla Topić, 2015) produced data that were analyzed to answer before mentioned research problems. The rest of two cognitive-psychology scales were used to define study sample.

MID-KOGTESTER1 has been used to evaluate the indicators of task performance dynamics in three variously simple cognitive-motor tests. This instrument is a computer-based battery of eight simple visual-motor tests for the assessment of the control and rate of human information processing, and aspects of working memory. In this study, three tests were used: Simple reaction time (SRT) test, Word recognition go-no go test (WR) and Choice reaction time (CRT) test.

MID-KOGTESTER1 components are:

(1) A laptop with an installed program designed to generate stimuli and record the subject's responses, i.e. reaction time (RT) in milliseconds. The RT is recorded separately for the cognitive and motor components of the response (according to the Hick paradigm), and errors are recorded. The program differentiates correct answers after error from correct answers after previous

correct answer and calculates various performance dynamics indicators (PDIs).

Figure 1. MID KOGTESTER 1 instrument

(2) A computer monitors on which the stimuli are displayed in various colors. *Note:* The monitor based on LCD technology was not used to control interruptions in the rendering of visual stimuli, caused by periodic status checks by the computer's operating system.

(3) Two panels with response keys. On the upper surface of the first panel, there are five response keys, or target keys, and they are arranged in a semicircle with equal distances from the (semicircle's) center. In the semicircle's center, there is a start key for initiating the stimulus. On the upper surface of the second panel, there are three horizontally arranged keys at equal distances, with the central key having the function of task starting. In answering the tasks of the study tests (SRT, WR, and CRT) only the first response panel has been used.

SRT, WR, and CRT tests consisted of *trial sequence* and *testing sequence* of various numbers of elementary cognitive tasks (ECTs).

The SRT test contains 20 ECTs in a testing sequence, with a previous trial sequence of 10 of them. As a stimulus, six identically colored characters X, in red, white, blue or green, appear on the monitor, in random order and with an unpredictable appearance interval (0.75 - 2.5 seconds). The participant's task is to raise the index finger as quickly as possible from the start key and press the target key, which is located vertically above the start key, as soon as (s)he notices the appearance of Xs of any color.

The WR test contains 30 ECTs in the testing sequence, with a previous trial of 10 ECTs. As a stimulus, a word (written in magenta color) appears on the monitor representing the name of one of the four colors (BLUE, GREEN, WHITE, and RED), or the word COLOR. The word COLOR is the target stimulus to which the participant must respond as soon as possible, and the color names are distractors to which the participant must not respond. The order of appearance of the target stimulus in relation to the distractors is random, and the time between the end of responding and the appearance of a new stimulus varies randomly (0.75 -2.5 seconds). The participant's task is to raise the index finger from the start key as quickly as possible and press the same target key, which is located vertically above the start key, after the target stimulus appears. If a distractor appears, the participant must not lift her/his finger from the start key, but wait patiently for the distractor to disappear. Although this test primarily measures cognitive inhibition function, it also represents a choice reaction test with two choices - to respond to the target stimulus, or not to do so to the distractor.

The CRT test contains 32 ECTs in a testing sequence, and 12 of them in the previous trial sequence. The stimuli are the names of colors (BLUE, GREEN, WHITE, and RED) written in magenta color and appear in a random order with an unpredictable interval between the end of responding and the appearance of a new stimulus (0.75 - 2.5 seconds). The participant responds to one of the four target keys, according to the rule given during the previous specific instruction. The participant's task is, after perceiving the color name on the monitor, to raise the index finger as quickly as possible from the start key and press the target key in accordance with the specific rule. This is a four-choice RT test since it demands from participant to respond to the appearance of one of four different color names by pressing one of four different keys.

Discriminability of the MID KOGTESTER-1 is very high since the RTs are measured with the precision of one millisecond (SRT, as the simplest test differentiated 97% of the tested participants). Test-retest reliability with one-year time lag ranged from 0.722 (SRT test) to 0.787 (WR test), which is very satisfactory.

After recording all participants' responses in the test, MID KOGTESTER-1 calculates PDIs (*performance dynamics indicators*).

Minimal RT (or best performance) in all three tests is denoted as *ct0min* and is defined as the shortest response time of the cognitive component of correct response after previous correct response on ECT (T^0) of the test SRT (*ct0min_1*), WR (*ct0min_2*) and *CRT* (*ct0min_3*). It is represented in milliseconds and the calculation formula is presented in Appendix 1.

Maximal RT (or worst performance) in all three tests is denoted as *ct0max* and is defined as the longest response time of the cognitive component of correct response after previous correct response on ECT (T^0) of the test SRT (*ct0max_1*), WR (*ct0max_2*) and *CRT* (*ct0max_3*). It is also represented in milliseconds and the calculation formula is written in Appendix 1.

Mean RT (or average task-solving performance) in all three tests is denoted as *cat0* and is defined as the average time of the cognitive component of correct response after the previous correct response on ECT (T^0) of the test SRT (*cat0_1*), WR (*cat0_2*) and *CRT* (*cat0_3*). This indicator is calculated by using T^0 and the number of all correct responses after the previous correct response (N^0) and it is represented in milliseconds. The calculation formula is presented in Appendix 1. Note: *cat0* presents an inverse measure of average task performance (larger *cat0* means worse average task performance).

Mean deviation of response time from the best RT (or average time of non-optimal cognitive task solving, i.e. average non-optimal performance instability) in all three tests is denoted as *catnof0* and is defined as the average time of non-optimized cognitive functioning during correct answering of ECTs of the test SRT (*catnof0_1*), WR (*catnof0_2*) and CRT (*catnof0_3*). It represents the average deviation of the cognitive component of RT in all correct answers (given after the correct answer), from the cognitive component of the best answer. It is represented in milliseconds and the calculation formula is written in Appendix 1.

The other two instruments were cognitive-psychology scale and checklist that were used to select appropriate sample of the target population: right-handed pupils of the age range 8-17 years, without health confinements relevant for visual-motor answering on elementary cognitive tasks.

Hand dominance scale (Tadinac, 1993), consisting of 12 questions considering which hand participant uses in 12 common life situations (e.g. *Which hand do you write with?*, or *Which hand do you hold the scissors with when cutting?*), was conducted to determine students' hand dominance, since only right-handed students participated in the study (85-90% of the population). Participants responded by selecting one of five possible answers *(-2 = always with left, -1= usually with left, 0= with one and the other hand, 1= usually with right, 2 = always with right*) and they were classified as right-handed if the total score (on all 12 questions) was higher than 8. The questionnaire was administered in groups, in each class separately. The author of the scale (Tadinac, 1993) did not report psychometric characteristics of the scale (reliability, validity), but insight in the related results within our study suggests that there were no statistical preconditions for doing that. Namely, standard psychometric calculation of reliability and validity coefficient is based on Pearson correlation among response values of the instrument's items (questions/statements) and the most of prerequisite assumptions for Pearson correlation calculation were violated in data measured by *Hand dominance scale administration* (highly asymmetric and bimodal distribution, variability reduced to only 5 values, sub-interval measurement scale).

Students' health status scale (Žebec, 2005), consisting of 12 questions, was conducted to determine students' health status focused on health characteristics relevant to cognitive-motor functioning (e.g. *Does your child distinguish colors well?*, or *Does your child have persistent or frequent difficulties with attention?*). The scale completed the parents of student-participants of the study, one or both of whom were present at the parent-teacher conference organized before other cognitive functions measurements (primarily necessary to determine the final sample of participants). Parents responded by answering "yes" or "no" and if their answers confirmed more than one relevant health problem, the child was not included in the research

sample (one confirmed health problem was taken into account when conducting the MID-KOGTESTER 1 measurement). Psychometric characteristics of the scale (reliability, validity) were not calculated because the scale was conceptualized as heterogenous checklist with rigorous exclusion criteria, not as standard questionnaire.

Research design

Measurements were part of the larger developmental study (Žebec et al, 2015) and were organized by using two research designs:

(1) *cross-sectional correlational design* ensured data collection needed for answering the first study problem (dependence among four indicators of cognitive task performance and inferring on their separate contribution to related cognitive functioning description)

(2) complex quasi-experimental mixed design with between-groups component (defined by independent variables of age, developmental phase, and sex) and within-subjects component (defined by independent variables of PDI's type and task complexity), enabled data collection needed for answering all other research problems (main and interaction effects of age/developmental phase, sex, task complexity and PDI's type on indicator's magnitude). Additionally, the observed, or dependent variables (DVs) were values of four PDIs (*best*, *worst* and *average performance*, and *non-optimal performance instability*), while independent variables (IVs) were previously mentioned in quasi-experimental mixed design.

Participants

The research participants were students of one elementary and one high school in the City of Zagreb, and as such they represent a convenient sample from the population of healthy children and youth aged 8 to 17, in urban areas of the Republic of Croatia. Based on the health status of the participants recorded by the scale, those whose health problems may be relevant to the subject of measurement or are of such a nature that it is not possible to speak with certainty about normal cognitive development, are excluded. A total of 463 right-handed participants took part in the study (228 were girls) and a more detailed age and sex structure is shown in the following table.

Table 1. Age-sex structure of study participants' sample

		sex		Total
		female	male	
age	8	34	46	80
	9	28	33	61
	10	17	6	23
	11	25	30	55
	12	19	16	35
	13	28	29	57
	14	8	12	20
	15	27	23	50
	16	21	19	40
	17	21	21	42
Total		**228**	**235**	**463**

Note: The age-sex groups associated with the ages of 10, 12, and 14 are noticeably less numerous than other age groups for two reasons: (1) the research was organized so that only 6 school ages were included - 2nd, 3rd, 5th, and 7th grade of elementary school and 1st and 3rd grade of high school; (2) in each of the 6 examined school ages, one age was dominant, but - due to the specific relationship between the date of birth and the date of measurement - part of the students of the given school age moved to "neighboring" age groups. In this sense, numerical uniformity of age and sex groups was not expected *a priori*.

Institute of the Improvement of Education at The *Ministry of Education and Sports of Republic of Croatia* has ethically approved the study, and the parents of the students, study participants, gave informed consent.

Procedure

In the first part of the research (as preparation for ECT performance measurement via MID KOGTESTER-1), *Hand dominance* and *Health status scales* were applied. Due to the organization of the stimuli on the MID KOGTESTER-1, which is adapted to right-handed people, participants with a dominant left hand were excluded from the study. Additionally, those with health dysfunctions that could be relevant for the measurement validity (for example, color blindness or hand motor disorders) or for the aim of measurement, i.e. normal cognitive development (for example, brain damage or color blindness) were also excluded from the study sample.

In the main part of the research, an individual examination was conducted for the duration of one school hour. It was done in school classrooms, specially organized to ensure the conditions of undisturbed individual examination. Before starting the MID KOGTESTER-1 tests, the participants were given a general instruction about the instrument, which explained the basic concept of the measurement, the content of the stimuli that appear on the screen, the way to answer on the answer boards, and the different types of errors when answering and the accompanying warning sounds. Additionally, before each ECT test (SRT, WR, CRT), they received specific instructions for solving it, in which the participant gets to know in detail the relevant stimuli and the specific way of responding to each of them. Moreover, they were advised to sit comfortably on the chair in front of the instrument in a position that would enable them to clearly perceive the stimuli and answer the tasks accurately and quickly, and to ignore potential distractors. Before each test, a trial sequence of the corresponding ECT was conducted in order for the participants to familiarize themselves with the stimuli and practice the way of answering, and to eliminate the possibility of misunderstanding the specific instructions.

During solving the MID KOGTESTER-1 test the participant dictates the pace of assigning tasks, because the display of the stimulus item starts only after the participant places the index finger on the start key. Initially, a fixation point appears on the monitor for a duration that randomly varies from 0.75 to 2.5 seconds. It has the function of a warning signal since it announces the stimulus appearance, and the participant is obliged to look at the point. After the stimulus appears on the monitor, the participant should raise the index finger from the start key as quickly as possible, press the corresponding target key, and then return the index finger to the start key. At the same time, the computer measures the time from the stimulus rendering until the moment the index finger is lifted from the start key (*cognitive processing time*) and from the moment the index finger is lifted from the start key until the target key is pressed (*movement time*). In addition, various possible errors are registered and followed by a sound warning, after which the subject returns the index finger to the start key and waits for a further stimulus.

Before the test, the importance of accuracy first, and then speed, is emphasized to the participants. The tests do not always appear in the same order, so STR can be the 1st or 2nd test, WR the same, and CRT the 3rd, 4th, or 5th test in order in the entire battery of eight tests, which varies from participant to participant (control of the exercise in within-subjects research design). In addition, the four possible layouts of target keys for the color are changing across the participants, thus controlling the strategy transfer among them and reducing the possible effect on test performance.

Results

Data were previously screened for outliers and then statistically processed by the IBM SPSS statistical package. All dependent variables (DVs) were measured as ratio scale data and therefore we used predominantly parametric inferential statistics (except in cases when other presumptions were significantly violated).

Statistical analyses were organized in relation to research problems but in the developmental aspect it differentiated two types of analysis: (1) *Age-related analysis* of the cognitive indicators of tasks performance dynamics (*Research problem 2*), (2) *Developmental phase's related analysis* of the same indicators (*Research problems 1, 3, 4 and 5*). This differentiation has been partially generated by violation

of factorial ANOVA assumptions related to equal age-sex sample sizes and homogeneity of variances, if we have used age as independent variable (IV) in answering *Research problems 3, 4 and 5*. Nevertheless, the differentiation of developmental statistical analysis primarily shaped the theoretical framework of cognitive development, which states that developmental changes mainly occur between successive developmental phases (Demetriou et al., 2018). On the other hand, within developmental phases, there should be no significant change, i.e. cognitive functions and their relations should be mostly stable.

Research problem 1 analysis and related results

In order to check if the four indicators of the cognitive component of simple cognitive-motor task solving *separately contribute* to dynamics description of related cognitive sub-system functioning, we applied correlational analysis. Namely, if these indicators represent mostly separate aspects of performance dynamics, then they should represent mostly independent dimensions of variable-vector space for dynamics description. In other words, *ct0min*, *ct0max*, *cat0,* and *catnof0* should not be highly correlated, i.e. they should not share more than 50% of the variance.

To calculate correlations among four indicators on homogenous participants' samples (to avoid the effect of developmental variables that modify the correlations as a hidden third variable) we decided to perform calculations on participants' subsamples defined by cognitive developmental phases. Namely, DVs are cognitive variables and within these phases cognitive and relevant variables should be mostly stable. By using Demetriou et al (2018) theoretical model of cognitive development, we identified four developmental phases (Dev.Phase) in our participants' sample: (i) 6 – 8 years (*emerging rule-based representations*), n_{DP1}=80; (ii) 9 – 11 years (*integration of rules into rule-based systems*), n_{DP2}=139; (iii) 12 – 13 years (*emerging principle-based representations*), n_{DP3}=92; (iv) 14 – 17 years (*integrated principles*), n_{DP4}=152.

On these subsamples, we calculated Pearson's correlations on all six pairs of PDIs at all three tests (SRT, WR, CRT). Applying calculation on various tests would raise the generalizability of the research problem findings. The results of this calculation are given in Table 2.

Table 2 reveals several important findings:

(1) Around 95% (of 72) of correlations were statistically significant and all *insignificant* ones were correlations between *ct0min* and *catnof0.*

(2) The average of all correlations was 0.599 meaning that the average percentage of shared variance (or common factors of the variables) among PDIs equals 35.9%.

(3) The weakest correlation stands between *ct0min* and *catnof0* (average *ct0min-catnof0* correlation across tests and Dev. Phases was 0.219).

(4) The strongest correlation stands between *cat0* and the other three indicators, depending on the test: (a) in SRT test r(*cat0-ct0min*)= 0.807, (b) in WR test r(*cat0-ct0max*)= 0.704 and (c) in CRT test r(*cat0-catnof0*)= 0.842.

(5) In most of the tests (i.e. SRT and WR) the strongest correlation appears in 2nd Dev. Phase, while in most of the tests (i.e. SRT and CRT) the weakest correlation appears in 4th Dev. Phase.

Research problem 2 analysis and related results

Since previous correlational analysis suggested that all observed performance dynamic indicators, except *average performance*, mostly reflect activation of specific combination of neurocognitive resources, we found it interesting to check whether these resources show specific developmental trajectories in the age range 8 – 17.

In order to do that, we rendered age-related trajectories of four indicators (*cat0*, *catnof0*, *ct0min*, *ct0max*) in all three tests (SRT, WR, CRT), separately for girls and boys. These trajectories are shown in the next 12 figures following Table 2.

Table 2. Pearson inter-correlations of four indicators of cognitive performance dynamics (*ct0min, ct0max, cat0, catnof0*) in three simple cognitive-motor tasks of various complexity (SRT, WR, CRT) across four theoretically based developmental phases (Dev. Phase).

test type	correlational pairs	Pearson correlation (r)			
		1. Dev. Phase	2. Dev. Phase	3. Dev. Phase	4. Dev. Phase
SRT	ct0min - ct0max	0.517**	0.582**	0.589**	0.474**
	ct0min - cat0	0.790**	0.798**	0.786**	0.853**
	ct0min – catnof0	0.413**	0.417**	0.213*	0.246**
	ct0max – cat0	0.661**	0.782**	0.858**	0.707**
	ct0max – catnof0	0.694**	0.751**	0.709**	0.706**
	cat0 – catnof0	0.834**	0.817**	0.640**	0.612**
WR	ct0min - ct0max	0.238*	0.391**	0.343**	0.386**
	ct0min - cat0	0.642**	0.700 **	0.594**	0.772**
	ct0min – catnof0	-0.033	0.067	-0.223*	-0.126
	ct0max – cat0	0.631**	0.769**	0.71**	0.705**
	ct0max – catnof0	0.696**	0.69**	0.614**	0.609**
	cat0 – catnof0	0.532**	0.453**	0.458**	0.418**
CRT	ct0min - ct0max	0.381**	0.613**	0.757**	0.361**
	ct0min - cat0	0.675**	0.797**	0.853**	0.648**
	ct0min – catnof0	0.391**	0.559**	0.647**	0.062
	ct0max – cat0	0.695**	0.849**	0.876**	0.829**
	ct0max – catnof0	0.804**	0.851**	0.810**	0.846**
	cat0 – catnof0	0.814**	0.883**	0.941**	0.731**

*Legend: * denotes statistical significance at p≤0.05, while ** denotes statistical significance at p≤0.01.*

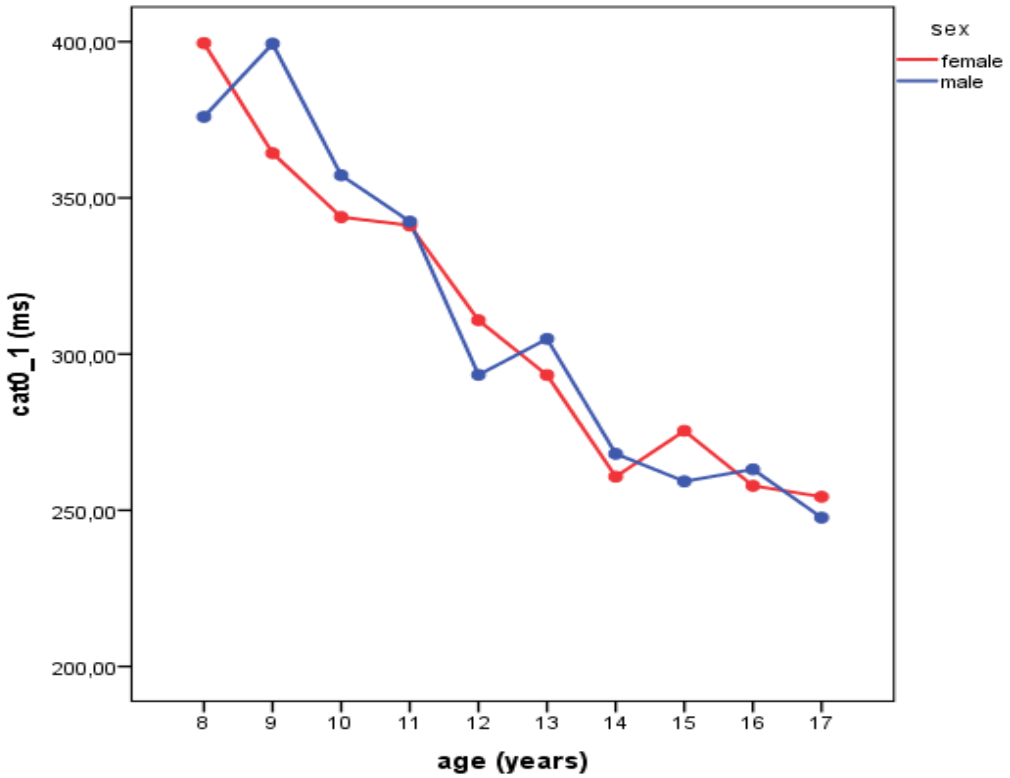

Figure 2a**.** Age-related differences of average cognitive response time in correct answered tasks of *Simple reaction time test* (cat0_1) for female and male students

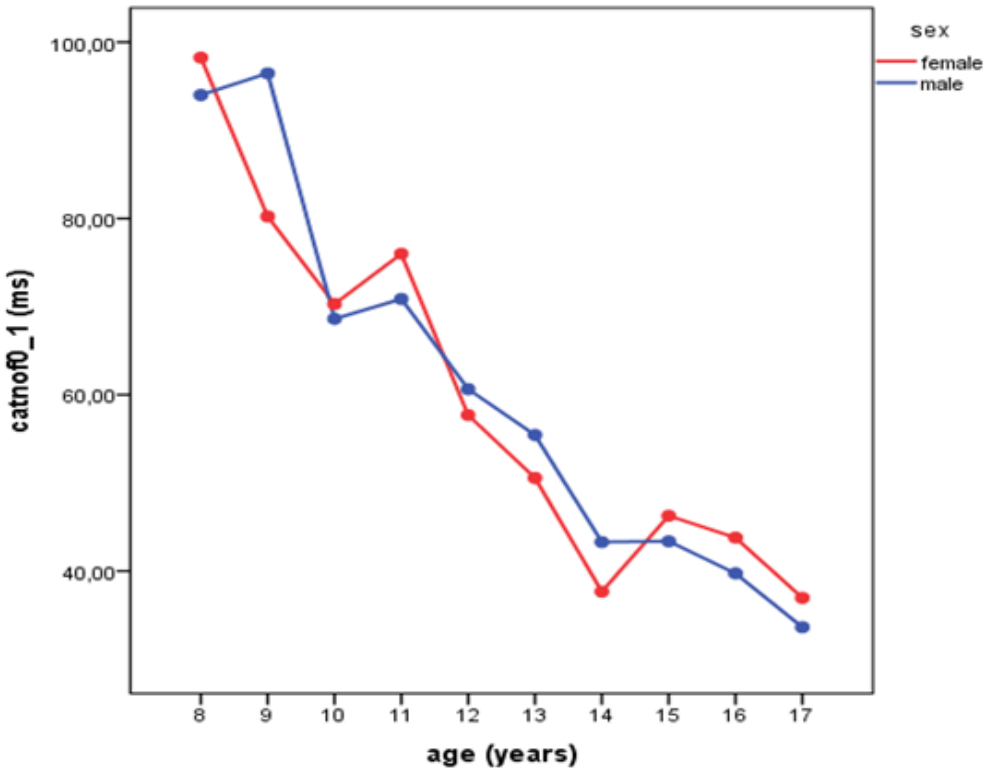

Figure 2b**.** Age-related differences of average non-optimized cognitive response time in correct answered tasks of *Simple reaction time test* (catnof0_1) for female and male students

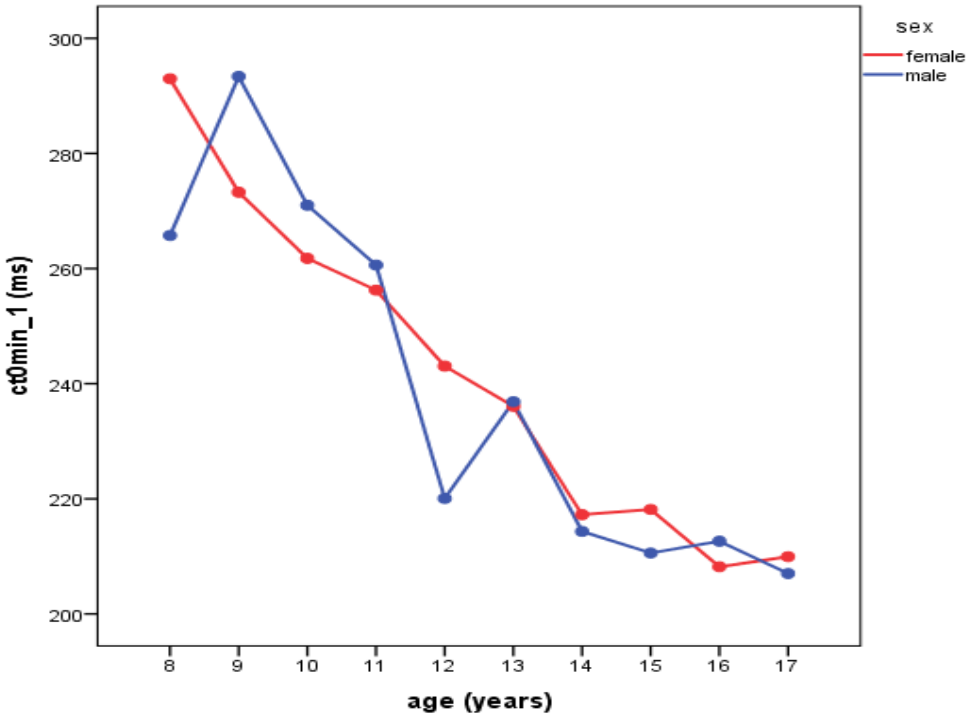

Figure 2c. Age-related differences of minimal cognitive response time in correct answered tasks of Simple reaction time test (ct0min_1) for female and male students

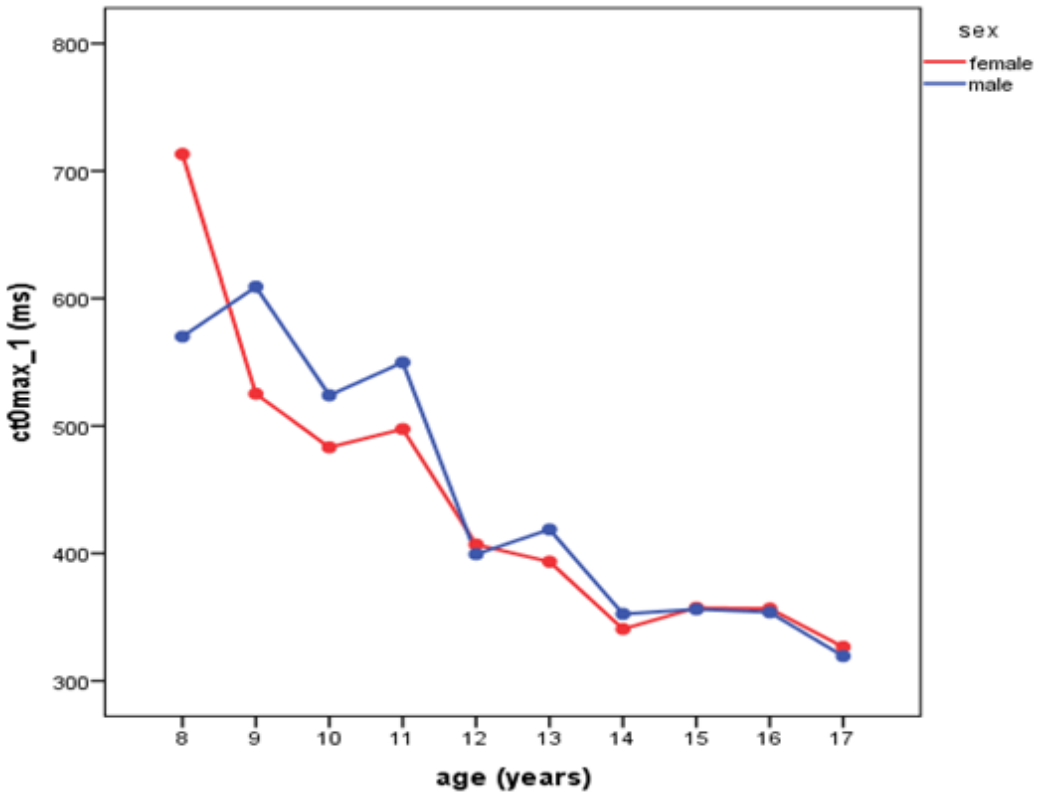

Figure 2d. Age-related differences of maximal cognitive response time in correct answered tasks of *Simple reaction time test* (ct0max 1) for female and male students

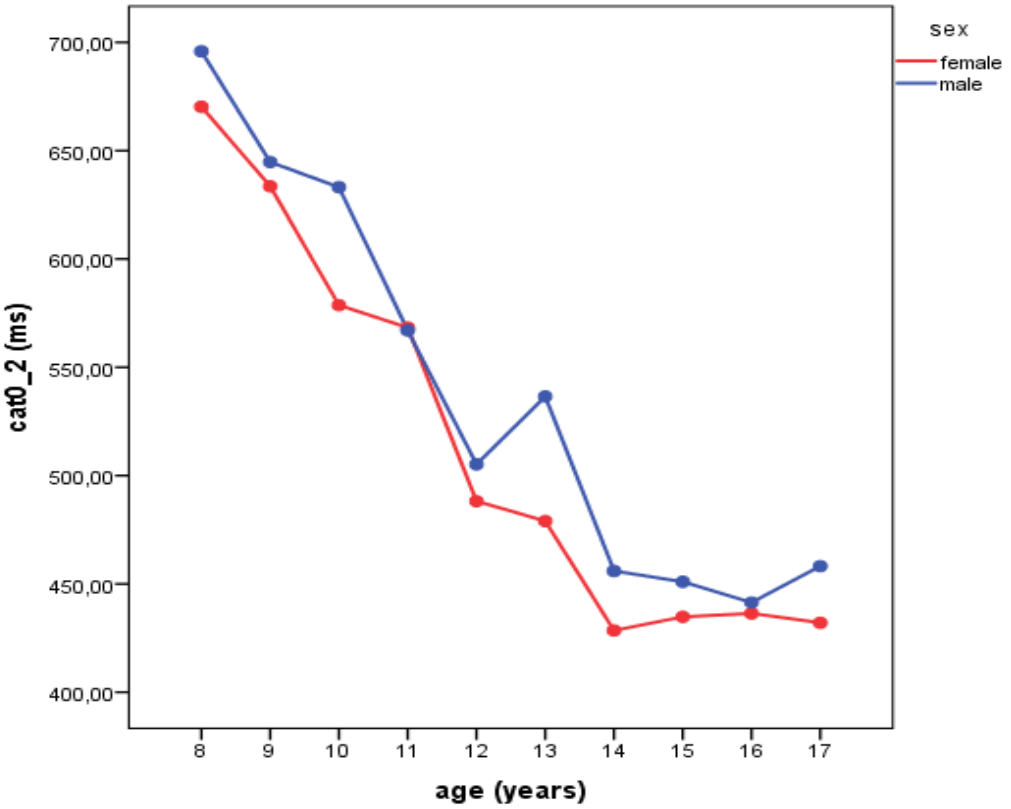

Figure 3a**.** Age-related differences of average cognitive response time in correct answered tasks of *Word recognition go-no go test* (cat0_2) for female and male students.

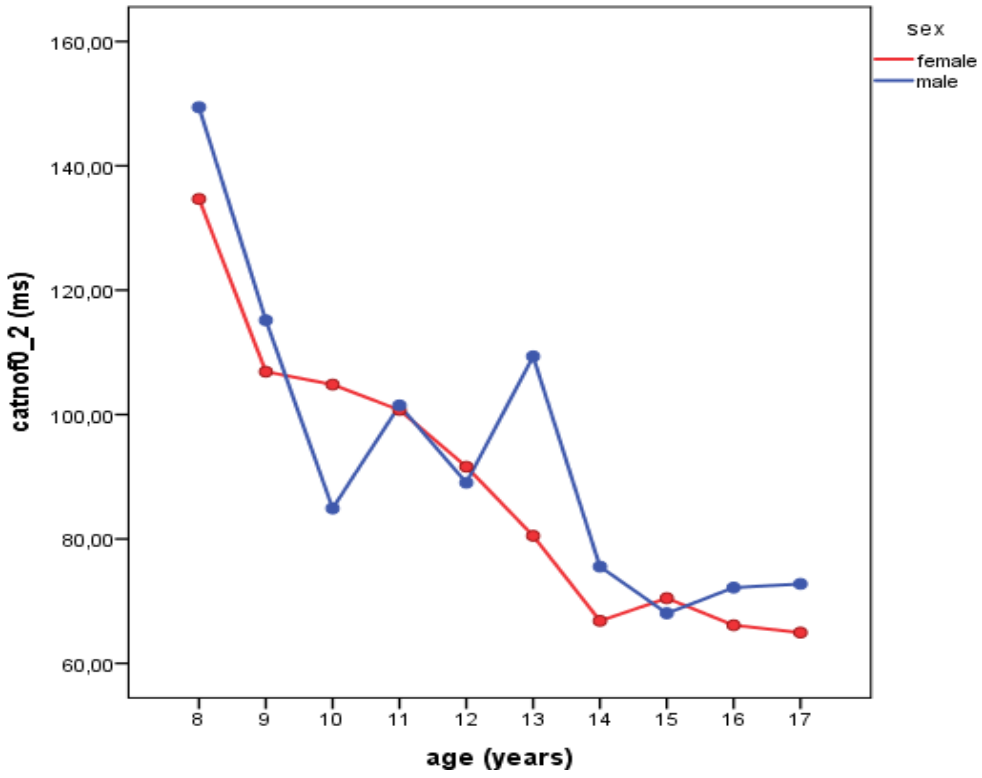

Figure 3b. Age-related differences of average non-optimized cognitive response time in correct answered tasks of *Word recognition go-no go test* (catnof0_2) for female and male students.

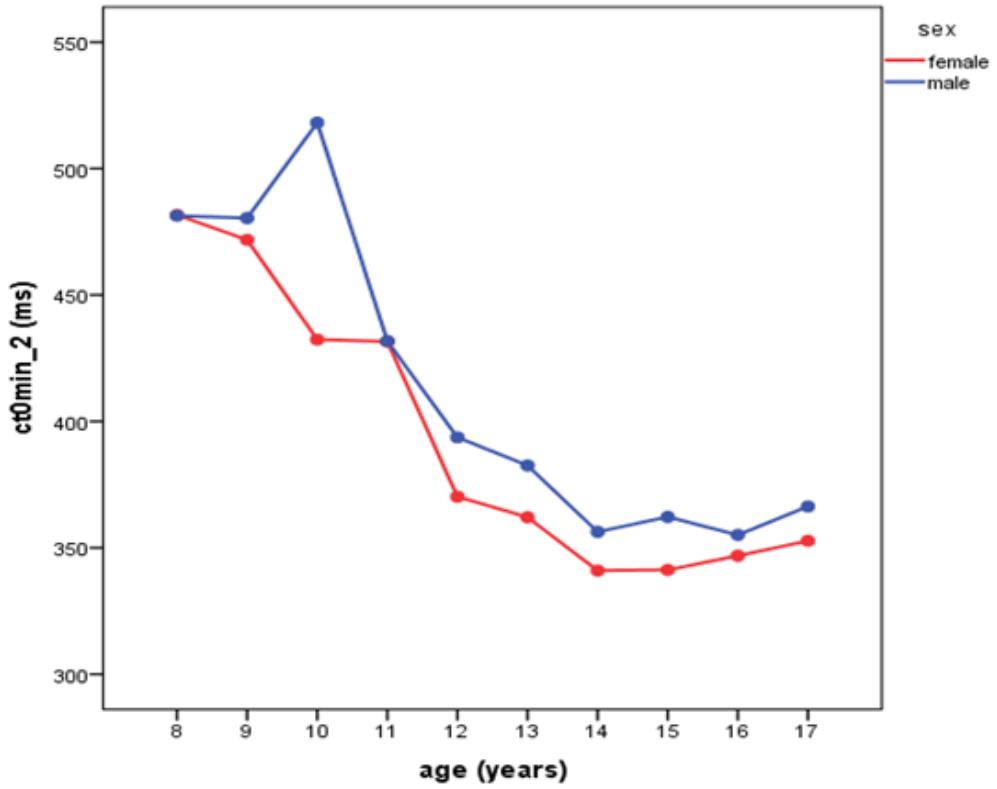

Figure 3c. Age-related differences of minimal cognitive response time in correct answered tasks of *Word recognition go-no go test* (ct0min_2) for female and male students.

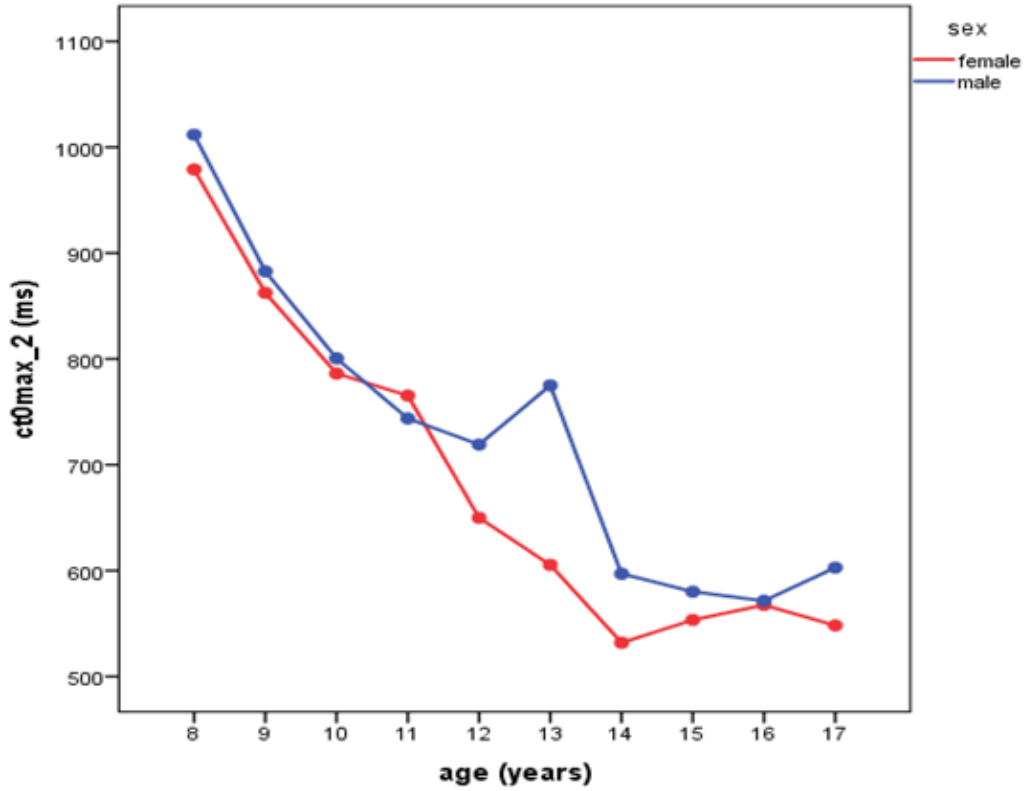

Figure 3d. Age-related differences of maximal cognitive response time in correct answered tasks of *Word recognition go-no go test* (ct0max_2) for female and male students.

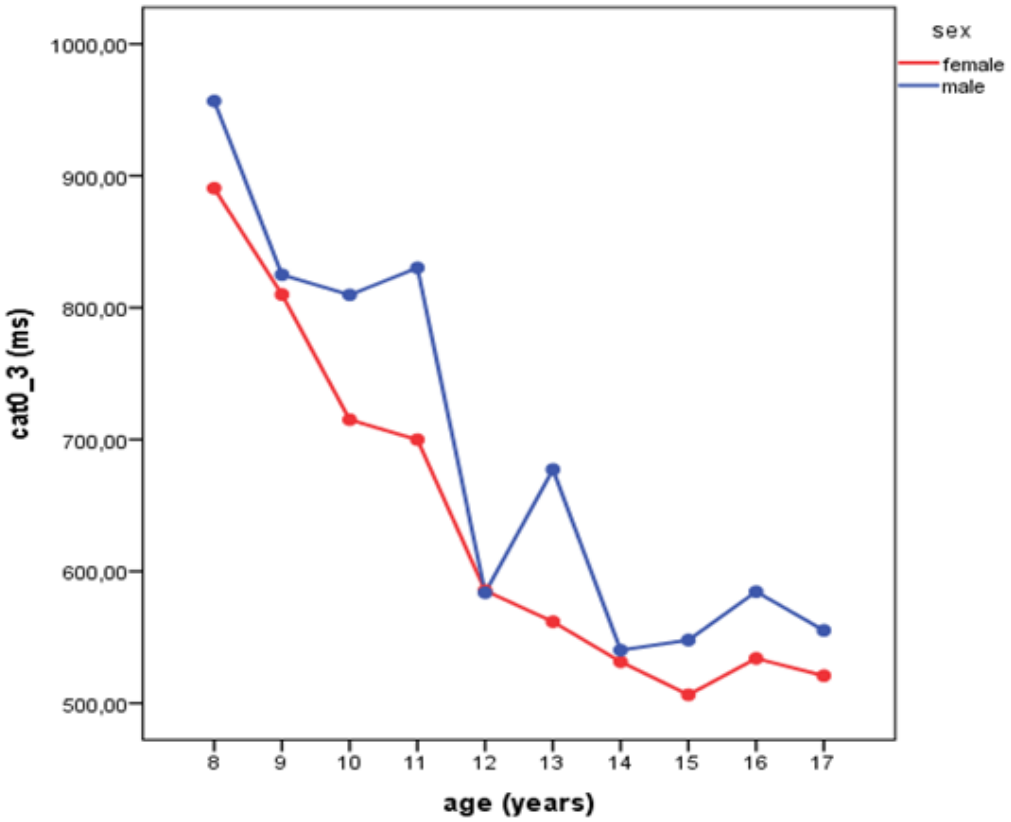

Figure 4a. Age-related differences of average cognitive response time in correct answered tasks of *Choice reaction time to the color name test* (cat0_3) for female and male students.

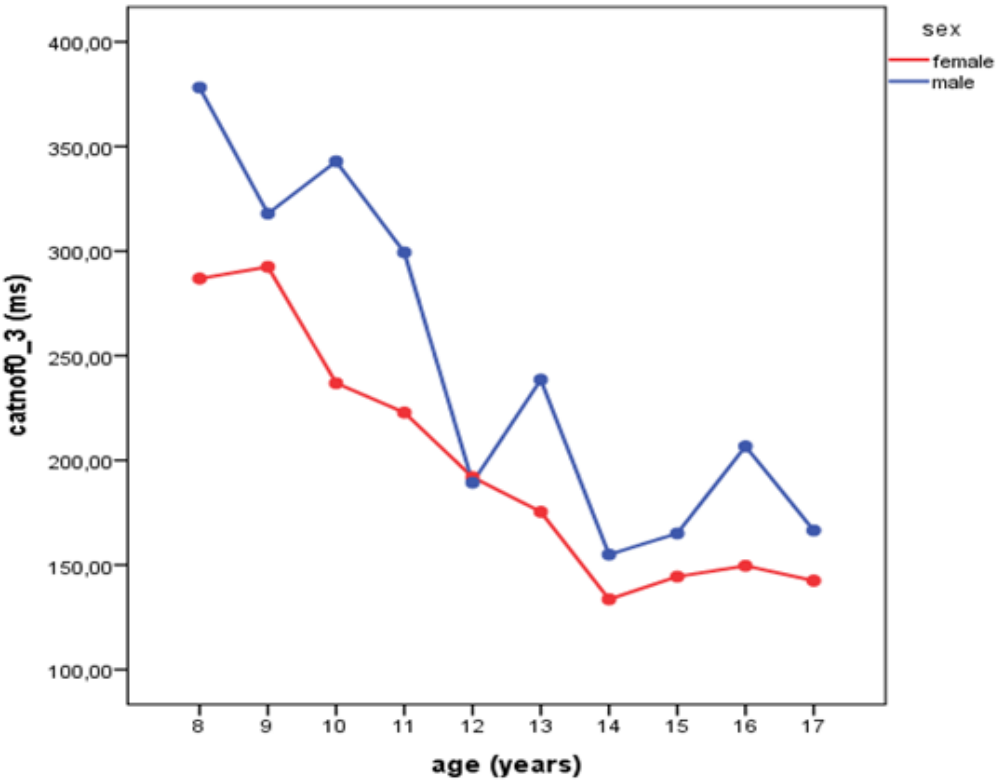

Figure 4b. Age-related differences of average non-optimized cognitive response time in correct answered tasks of *Choice reaction time to the color name test* (catnof0_3) for female and male students.

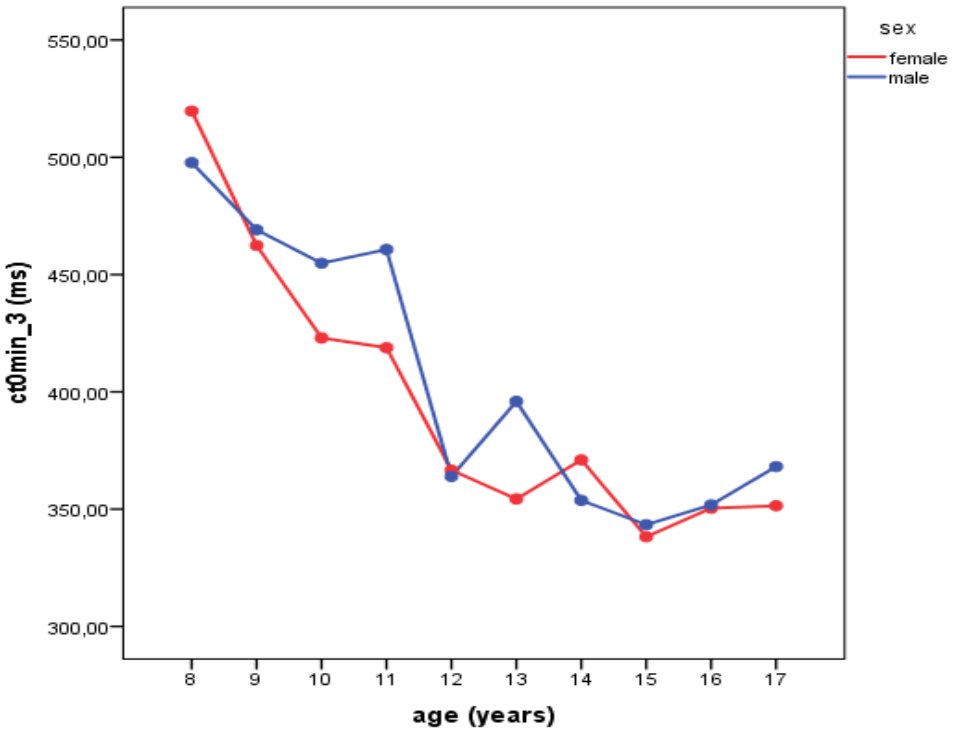

Figure 4c. Age-related differences of minimal cognitive response time in correct answered tasks of *Choice reaction time to the color name test* (ct0min_3) for female and male students

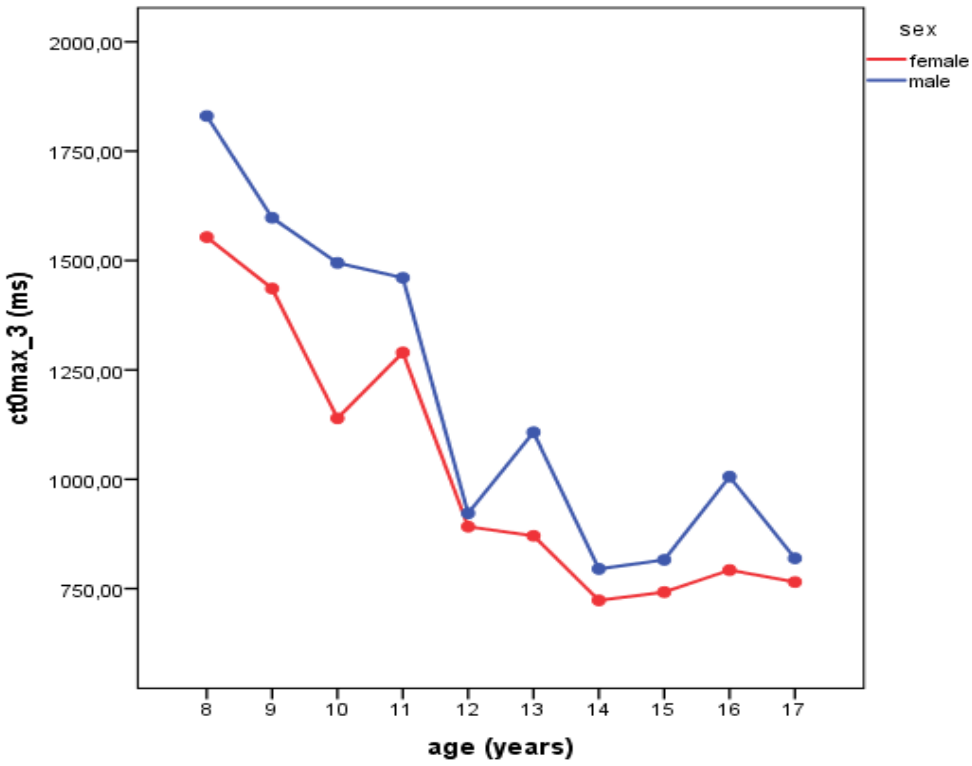

Figure 4d. Age-related differences of maximal cognitive response time in correct answered tasks of *Choice reaction time to the color name test* (ct0max_3) for female and male students.

By analyzing *Figures 2a – 2d*, *Figures 3a – 3d*, and *Figures 4a – 4d*, related to sex-specific age-related differences of PDIs in *SRT, WR and CRT test*, we derived several findings:

(1) Values of all four PDIs decrease in the observed developmental period; considering that smaller PDI value means better performance, all four PDIs improve in the observed period,

(2) The smallest relative decrement from age 8 to age 17 (i.e. absolute indicator's decrement divided by the average value of the indicator) is found at *ct0min* indicator,

(3) The largest relative decrement from age 8 to age 17 is found at *catnof0* indicator in SRT and WR tests and is found at *ct0max* indicator in CRT test,

(4) Sex differences in PDI's values in the observed developmental period increase from SRT task to CRT task and are present at ages of 9-10, 12-13 and 17 years for most of PDIs; More precisely:

- in SRT test the observed sex differences are not clearly expressed, although there is indication that girls show better performance until the age 12 or 13 years,

- in WR test girls perform better at age 10 (in *cat0* and *ct0min*) and at ages 12-14 (in all PDIs)

- in CRT test girls perform better at ages 10-11 and at ages 13-16, in the most of PDIs

(5) The age-related means variation across observed successive ages of most of the PDIs has been more pronounced in boys, but this tendency is more clear in WR and CRT tests, then in SRT test (where girls' means varied more for *cat0* and *catnof0*, while boys' means varied more for *ct0min* and *ct0max*),

(6) Age-related changes in PDIs are non-linear since their mean decrement from 8 to 12 years of age is several times larger than their decrement from 12 to 17 years (depending on the indicator); thereby the smallest nonlinearity has been found mostly at *catnof0* (in WR and CRT tests), while the largest one has been found at *ct0min*. Additionally, nonlinearity grows with test complexity. More precisely, in:

- SRT test (age related decrement)$_{8\text{-}12}$ is 1.5 – 2.8 times larger than (age related decrement)$_{12\text{-}17}$

- WR test (age related decrement)$_{8\text{-}12}$ is 2.5 – 4.8 times larger than (age related decrement)$_{12\text{-}17}$

- CRT test (age related decrement)$_{8\text{-}12}$ is 4 – 24 times larger than (age related decrement)$_{12\text{-}17}$

Research problem 3 analysis and related results

To statistically test specificities of four PDIs' developmental trends (related to developmental change intensity, to cognitive-motor task complexity, and to children's/youth's sex) revealed by previous descriptive statistical analysis, we conducted ANOVA statistical procedures. Thereby we analyzed these trends across cognitive Dev. Phases (not across developmental ages) to satisfy ANOVA prerequisites and theoretical guidelines of cognitive development.

(i) Possible specificities of various PDIs development across cognitive Dev. Phases

To test whether four PDIs (*best*, *worst* and *average performance* and *non-optimal performance instability*) change with different intensity across four cognitive Dev. Phases, we performed analysis that included relation to participant's sex and relation to task complexity (independent variables that possibly determine differential PDIs decrement across Dev. Phases). Therefore, we performed two models of three-way ANOVA: **(1)** (*Dev. Phase*) X (*PDI's type*) X (*participant's sex*) and **(2)** (*Dev. Phase*) X (*PDI's type*) X (*task complexity*). First ANOVA model is conducted separately for three variously complex cognitive-motor tasks

(*SRT, WR, CRT*), while second ANOVA model included task complexity as one of three independent variables of the model. The target outcomes of these four ANOVA calculations (three calculations of the 1st three-way ANOVA model, and one calculation of the 2nd three-way ANOVA model) were interactional effects (*Dev Phase)* X (*PDI's type)* on PDI's values, and they are presented in *Table 3*.

Table 3. Outcomes of two models of three-way repeated measures ANOVA calculation related to interaction effect of *PDI's type* and *Dev. Phase* on PDIs' values (with first model conducted for all three cognitive-motor tasks - *SRT, WR, CRT*).

three-way ANOVA model	Test complexity	df_1	df_2	Mean Square	F	Sig.	Partial Eta Squared	Observed Power
	Outcome of interaction effect of *PDI's type* and *developmental phase* on PDIs' values							
***(1)** DevPhase* X *PDIType* X *Sex*	SRT	3.61	548.20	657010.109	58.051	<0.001	0.277	1.000
	WR	4.85	735.88	874601.700	87.062	<0.001	0.365	1.000
	CRT	3.36	508.07	7091459.432	37.901	<0.001	0.200	1.000
***(2)** DevPhase* X *PDIType* X *Task complexity*	SRT WR CRT	3.48	531.29	3133686.701	23.567	<0.001	0.134	1.000

Note: interaction effects were calculated within two models of three-way repeated-measures ANOVA by using Greenhouse-Geisser correction of degrees of freedom (sphericity assumption violated).

Results of both models of three-way ANOVAs clearly show that four observed interaction effects (*PDI's type) X* (*Dev. Phase)* on PDI's values are statistically significant, which means that various PDIs values decrease across Dev. Phases with different intensities (or slopes). *Partial Eta Squared* values in ANOVA model (*1*) suggest that the strongest (*PDI's type)* X (*Dev. Phase)* interaction was observed at WR test and the smallest interaction is observed at CRT test. These differences in the observed interaction effects among variously complex tasks proved to be significant in ANOVA model (2) ($F= 16.810$, $df_1= 4.03$, $df_2= 614.71$, $p<0.001$).

To elaborate differences in decrement intensity of various PDI's across four Dev. Phases we performed 12 *one-way ANOVAs,* with Dev. Phase being the only independent variable, for all PDIs in three variously simple tasks (SRT, WR, CRT). *Partial Eta Squared* values (that give us information on the effect size that Dev. Phase exerts on PDI's values), presented in following *Table 3.1*, suggest that *Dev. Phase* produced the greatest decrement effect on *cat0* and the smallest decrement effect on *catnof0* (with *ct0max* being mostly on the third and *ct0min* mostly on second place). This finding is not aligned with some conclusions of the 2nd *Research problem analysis* (that stated the greatest *relative* developmental decrement for *catnof0*, and the smallest for *ct0min*) and this discrepancy stems from two sources. First, one-way ANOVAs are performed with *Dev. Phase* as independent variable, and relative decrement in 2nd *Research problem analysis* included *age* as independent variable. Second, *Partial Eta Squared* calculation is based on different elements then relative decrement calculation.

Table 3.1. One-way ANOVA statistical procedures outcomes conducted to assess PDIs' decrement (*ct0min, ct0max, cat0, catnof0*) across cognitive Dev. Phases in variously simple cognitive-motor tasks (SRT, WR, CRT).

Task's type	Performance dynamics indicator	df_1	df_2	Mean Square	F	Sig.	Partial Eta Squared	Observed Power
SRT	*ct0min_1*	3	459	117038.227	79.194	<0.001	0.341	1.00
	ct0max_1	3	459	1825302.006	75.545	<0.001	0.331	1.00
	cat0_1	3	459	382218.300	115.782	<0.001	**0.431**	1.00
	catnof0_1	3	459	67324.607	72.991	<0.001	*0.323*	1.00
WR	*ct0min_2*	3	459	430340.406	113.975	<0.001	0.427	1.00
	ct0max_2	3	459	3561253.32	146.699	<0.001	0.489	1.00
	cat0_2	3	459	1265585.14	209.876	<0.001	**0.578**	1.00
	catnof0_2	3	459	98751.700	82.950	<0.001	*0.352*	1.00
CRT	*ct0min_3*	3	458	547249.454	63.642	<0.001	0.294	1.00
	ct0max_3	3	458	18657973.3	49.842	<0.001	0.246	1.00
	cat0_3	3	458	3316738.35	73.468	<0.001	**0.325**	1.00
	catnof0_3	3	459	723555.193	41.694	<0.001	*0.214*	1.00

By considering that all PDIs are inverse measures of performance success (the longer decision times reflect worse performance of activated cognitive-motor system), the above mentioned ANOVA results point to developmental improvement of performance dynamics of the cognitive systems activated during solving three simple cognitive-motor tests (*SRT, WR, CRT*). The largest developmental improvement showed *average task performance* of the cognitive system, while the smallest improvement showed cognitive system *non-optimal functional instability*. These differences in developmental improvement among PDIs are the most expressive in WR cognitive-motor system and the least expressive in CRT cognitive-motor system.

At the end of this analysis of different intensities in four PDIs developmental improvement, it should be noted that differentiated improvement has the same form for girls and boys only in CRT task ($F= 0.530$, $df_1= 3.36$, $df_2= 508.07$, $p>0.05$). In SRT task ($F= 8.030$, $df_1= 3.62$, $df_2= 548.20$, $p<0.001$) and WR task ($F= 2.875$, $df_1= 4.85$, $df_2= 735.88$, $p<0.05$) differentiated improvement of four PDIs did not have the same form for both sexes. Namely, in SRT task performance, previously proved differentiated PDIs' developmental decrement, at girls is continuous/smooth from the first developmental phase, while at boys this differentiated PDI's decrement starts to be continuous/smooth from the second developmental phase. On the other hand, in WR task performance, previously proved differentiated PDIs' developmental decrement, at

girls contains steeper developmental decrement of *ct0max* and *cat0* indicators, than at boys.

(i) *Possible dependence of PDIs development on cognitive-motor task complexity*

To test whether developmental change of any PDI varies across cognitive-motor task complexity, we performed two-way repeated measures ANOVA for every PDI, with *Dev. phase* and *Task complexity* as independent variables and we focused to (*Dev. phase*) X (*Task complexity*) interaction effect.

Table 4. Outcome of two-way repeated measures ANOVA related to interactional effect of *task complexity* and *developmental phase* on PDIs' values, for all four PDIs (*ct0min, ct0max, cat0, catnof0*).

Indicator's type	df_1	df_2	Mean Square	F	Sig.	Partial Eta Squared	Observed Power
ct0min	4.90	748.73	61942.851	15.406	<0.001	0.092	1.000
ct0max	3.50	534.84	4383895.606	19.765	<0.001	0.115	1.000
cat0	3.51	543.46	633183.923	25.664	<0.001	0.144	1.000
catnof0	3.53	540.75	189161.491	18.670	<0.001	0.109	1.000

Note: interaction effects were calculated within a two-way repeated-measures ANOVA (*developmental phase* X *task's complexity*) by using Greenhouse-Geisser correction of degrees of freedom (sphericity assumption violated).

Table 4 results point to significant (*Dev. phase*) X (*Task complexity*) interactional effect on PDI's value at all PDI's types, which means that any observed PDI improves developmentally in a different way for differently complex cognitive-motor tasks. This finding is confirmed within two models of three-way ANOVA. (1) (*Dev. phase*) X (*Task complexity*) X (*Participant's sex*) ANOVA model showed that interaction effect of *Dev phase* and *Task complexity* on PDI's values is significant for all four PDIs (F_{ct0min}= 15.01, p<0.001; F_{ct0max}= 18.69, p<0.001; F_{cat0}= 24.55, p<0.001; $F_{catnof0}$= 17.76, p<0.001). (2) (*Dev. phase*) X (*PDI's type*) X (*Task complexity*) ANOVA model showed significance of the same interaction effect (F= 23.57, df_1= 3.48, df_2= 531.29, p<0.001).

The *Table 3.1* results tell us how the observed PDIs decrease across Dev. Phases differently at SRT, WR and CRT cognitive-motor task. Namely, *Partial Eta Squared* values of all four PDIs vary across task types with the same pattern: developmental change of all PDIs is the most present/obvious in WR task performance, and the least present/obvious in CRT task performance.

(ii) Possible dependence of cognitive PDIs' developmental change on participant's sex

Since the conclusions of the 2nd Research problem included possible sex differences in PDIs' values and in PDIs' development on the descriptive level, it is expected to statistically test (on inferential level) these differences in cognitive performance dynamics. To do that, we first changed the analytic scale from *ages* to *Dev. Phases*, and then calculated *(Dev. phase) X (Participant's sex)* interactions within three-way ANOVA model (*Dev. phase*) X (*Participant's sex*) X (*Task complexity*) for every PDI (*ct0min*, *ct0max*, *cat0*, *catnof0*). After that, we elaborated the obtained results within additional

two-way ANOVA calculations of the same *(Dev phase) X (Participant's sex)* interaction effects for every PDI, in every cognitive-motor task (*SRT, WR, CRT*).

Table 5. Outcomes of (*Dev. phase*) X (*Participant's sex*) X (*Task complexity*) ANOVA for all PDIs (*ct0min, ct0max, cat0, catnof0*) related to (*Dev. phase*) X (*Participant's sex*) interaction.

PDI type	df_1	df_2	Mean Square	F	Sig.	Partial Eta Squared	Observed Power
ct0min	3	454	15655.837	2.172	0.091	0.014	0.552
ct0max	3	454	75988.207	0.473	0.701	0.003	0.146
cat0	3	454	10175.976	0.411	0.745	0.003	0.132
catnof0	3	455	7289.194	1.006	0.390	0.007	0.274

Note: In calculating two-way interaction effect (*Dev. phase*) X (*Participant's sex*) on PDI-dependent variable, this variable is formed as the average of PDI_{SRT}, PDI_{WR} and PDI_{CRT} values.

Table 5 content states that *(Dev. phase) X (Participant's sex)* interaction is not significant at any PDI, which means that all PDIs improve across developmental phases in the same way for girls and boys. Since in this ANOVA model PDI-dependent variable (in the observed two-way interaction) is the average of three variously complex components (PDI_{SRT}, PDI_{WR} and PDI_{CRT} values), the obtained interaction effects do not say anything about the observed interaction effect on the level of particular task (*SRT, WR, CRT*). Therefore, we calculated 12 two-way ANOVAs (for every PDI, in every task) and presented the related results in *Table 5.1* in condensed form.

Table 5.1. Outcomes of two-way ANOVA calculation of interactions (*Dev. phase)* X *(Participant's sex)* for every PDI, in every cognitive-motor task (*SRT, WR, CRT*).

		Task type		
		SRT	*WR*	*CRT*
PDI	*ct0min*	F= 4.79 df_1=3 ; df_2=455 **p<0.01**	F= 0.46 df_1=3 ; df_2=455 p>0.05	F= 1.38 df_1=3 ; df_2=454 p>0.05
	ct0max	F= 8.36 df_1=3 ; df_2=455 **p<0.001**	F= 3.32 df_1=3 ; df_2=455 **p<0.05**	F= 0.43 df_1=3 ; df_2=454 p>0.05
	cat0	F= 2.59 df_1=3 ; df_2=455 p=0.052	F= 0.77 df_1=3 ; df_2=455 p>0.05	F= 0.26 df_1=3 ; df_2=454 p>0.05
	catnof0	F= 0.82 df_1=3 ; df_2=455 p>0.05	F= 1.26 df_1=3 ; df_2=455 p>0.05	F= 1.06 df_1=3 ; df_2=455 p>0.05

The findings of *Table 5.1* show that developmental improvement of PDIs still differs for girls and boys at *ct0min* and *ct0max* indicators during SRT task performance and at *ct0max* indicator during WR task performance. Conducting independent t-test at every Dev. Phase, to test the possible sex

differences in *ct0min* and *ct0max* at SRT and WR task, gave next findings. Sex differences were noted at first developmental phase in $ct0min_{SRT}$ and $ct0max_{SRT}$ (t= 2.714, df= 78, p= 0.008 and t= 2.216, df= 47.364, p= 0.031, respectively) and at second developmental phase only in $ct0max_{SRT}$ (t= -2.500, df=137, p= 0.014). Thereby, boys outperformed girls in $ct0min_{SRT}$ and $ct0max_{SRT}$ at phase 1, and girls were superior in $ct0max_{SRT}$ at phase 2. Furthermore, testing sex differences in *ct0max* of WR task (at every developmental phase), showed that girls' and boys' worst performance was the same during the first two Dev. Phases. However, girls outperformed boys during the last two observed phases (t_{phase1}= -0.662, df=77.97, p=0.510; t_{phase2}= -0.193, df=137, p=0.847; t_{phase3}= -5.419, df=76.84, p<0.001; t_{phase4}= -2.676, df=149.95, p<0.01).

Research problem 4 analysis and related results

Although the analysis of the 3rd Research problem proved that, there are sex differences in some PDIs' values at some developmental phases, the systematic analysis of sex differences in performance dynamics still have to be done. To do that, we conducted three-way repeated measures ANOVA (*participant's sex*) X (*PDI's type*) X (*task complexity*) and focused to sex differences on the observed developmental period as a whole, and their possible dependence on PDI's type and on task complexity. To elaborate results of this analysis, we conducted additional t-tests with *participant's sex* as independent variables.

The outcomes of the above mentioned three-way ANOVA, relevant for sex differences analysis, are given in *Table 6*.

Table 6. Outcomes of three-way repeated measures ANOVA (*participant's sex*) X (*PDI's type*) X (*task complexity*), relevant for sex differences analysis of performance dynamics in three variously simple cognitive-motor tasks.

Source of variation	df1	df2	Mean Square	F	p	Partial Eta Squared	Observed Power
participant's sex	1	460	2313856.18	10.632	0.001	0.023	0.902
(participan's sex) X (PDI type)	1.13	519.33	1191061.84	9.671	0.001	0.021	0.901
(participant's sex) X (task complexity)	1.15	531.01	1559605.26	10.384	0.001	0.022	0.924

Note: Testing prerequisite assumptions for repeated measures ANOVA showed that sphericity assumption has been violated, so we applied related Greenhouse-Geisser correction.

(i) *Sex differences in overall performance dynamics*

Main effect of participant's sex on PDIs' values, from *Table 6,* is significant and points to sex differences in performance dynamics while solving three variously simple cognitive-motor tasks. This effect is present in overall observed developmental period, but its size is small (Partial Eta Squared value shows that only 2.3% of total PDIs' variability is explained by sex differences).

To describe direction and structure of these sex differences in overall performance dynamics during completely observed developmental period, according to dimensions of PDI type and task complexity, we conducted 12 independent sample t-test (4 PDIs X 3 tasks). The results of these t-tests were presented in *Table 6.1* in the condensed form.

Table 6.1. Means (M) and standard deviations (SD) of PDIs' values in girls and boys, calculated on overall developmental period and distributed according PDI's type and task complexity.

		Task complexity					
		SRT		***WR***		***CRT***	
PDI	***ct0min***	M_f =246.1	SD_f=45.75	M_f =401.5	SD_f=77.69	M_f = 403.5	SD_f=101.68
		M_m=244.9	SD_m=48.67	M_m=419.1	SD_m=83.14	M_m=420.4	SD_m=117.13
		M_f-M_m= 1.2		***M_f-M_m = -17.6****		***M_f-M_m = -16.9***	
	ct0max	M_f =460.9	SD_f =204.29	M_f =709.9	SD_f = 208.59	M_f =1071.4	SD_f =613.54
		M_m =469.6	SD_m =173.99	M_m =769.3	SD_m =222.08	M_m =1281.7	SD_m =765.83
		M_f-M_m = -8.7		***M_f-M_m = -59.4****		***M_f-M_m = -210.3****	
	cat0	M_f =318.2	SD_f =72.76	M_f =529.2	SD_f =112.15	M_f =655.7	SD_f =234.98
		M_m =322.6	SD_m =78.94	M_m =559.9	SD_m =124.04	M_m =731.2	SD_m =273.39
		M_f-M_m = -4.40		***M_f-M_m = -30.7****		***M_f-M_m = -75.5****	
	catnof0	M_f =184.7	SD_f =149.88	M_f =92.4	SD_f =37.55	M_f =207.0	SD_f =123.39
		M_m =190.7	SD_m =168.99	M_m =102.9	SD_m =46.66	M_m =263.6	SD_m =164.20
		M_f-M_m = -6		***M_f-M_m = -10.5****		***M_f-M_m = -56.6****	

Notes: The difference in PDIs' mean values between girls and boys (Mf-Mm) has been tested with independent samples' t-test; *= p<0.05, ** = p<0.01.

Table 6.1 findings show that girls' PDIs' values are smaller than the ones from boys in 91% of the cases (differences M_f-M_m are negative), which means that girls' performance dynamics at the observed developmental period is superior to the boys' performance dynamics – although this difference is small.

(ii) Sex differences' dependence on PDI's type

Since interaction effect (*Participant's sex*) X (*PDI type*), presented in the *Table 6*, is statistically significant, it can be concluded that small girls' superiority in overall performance dynamics depends on PDI's type. To interpret this dependence, the magnitudes of statistically significant differences M_f-M_m of *Table 6.1* are used. Namely, from these magnitudes it is visible that the biggest girls' advantage appears at *ct0max* PDI, while the smallest girls' advantage appears at *ct0min* PDI.

(iii) Sex differences' dependence on task complexity

Finally, to infer if small, but significant girls' superiority in overall performance dynamics (and at overall observed developmental range) depends on task complexity, we refer to (*Participant's sex*) X (*Task complexity*) interaction effect. Findings on this effect from *Table 6* tell us that the observed sex differences significantly depend on cognitive-motor task complexity. The form of this dependence we derive from *Table 6.1* results: since differences M_f-M_m predominantly continuously increase from SRT-task to CRT-task, we conclude that small girls' superiority increases with cognitive-motor task complexity, in the observed developmental period.

Discussion

Concerning the 1st Research problem, there are several arguments that suggest that four PDIs of the cognitive component of simple cognitive-motor task solving separately contribute to description of related cognitive sub-system functioning. First, mutual PDIs' correlations, although positive and significant in the most

correlation pairs (across all three tasks and all four Dev. Phases), in average do not explain more than 36% of common variance (median value of all correlations suggests 45% of common variance). That means that, with exception of *cat0* correlations with other PDIs (whose average value of common variance is 52.6%), the other three PDIs mostly didn't share mutually more than 50% of the variance and therefore, mostly presented *specific and separate performance dynamics descriptors*. Due to the reliability of the measurement (which ranges from 0.72 to 0.79%), the question arises whether the percentage of shared variance among PDI constructs is greater than 36%, but there are also developmental reasons why this increase is not realistic to expect. Specifically, the correlations in *Table 2* were calculated within each developmental phase, and from the graphical representations of the 2nd *Research problem*, it is clear that within these phases all PDIs change (decrease) with age. Therefore, the *age variable* also acts in the background of all correlations in *Table 2*, due to which the correlations are partly increased. Therefore, the sum of the antagonistic effects of *measurement reliability* and *age* on the correlations of *Table 2* suggests that their estimate of the relationship among the four PDIs stays valid.

Average performance efficiency (i.e. *cat0*) logically showed higher correlations with other PDIs, while it incorporates other PDIs by its definition (i.e. calculation formula). Furthermore, significant positive mutual PDIs' correlations at almost all indicators (across the three variously simple tests and across four Dev. Phases) is also logical since they are calculated from the same individual's RT distribution. However, these four PDIs do not use the same part of individual's RT distribution in their calculation (the exception is *cat0* that uses the whole RT distribution) and therefore mutual correlations among PDIs are of confined magnitude. That suggest that these PDIs measure mostly different constructs of cognitive process activated during task responding. Additionally, *best performance* (*ct0min*) and *average non-optimal performance instability* (*catnof0*) calculation formula explains the lowest correlations between these two indicators: instability is average deviation of all RTs in individual's RT distribution from the best performance (and *X* cannot be highly correlated with *deviation from X*).

The last finding of the 1st problem analysis shows that PDIs are somewhat largely correlated in first two Dev. Phases (average r= 0.615) than in the last two (average r= 0.584), which can be explained by more intensive age-related change of all indicators in the first two Dev. Phases (see Figures 2a – 4d). Namely, within these two phases *age*, as a third variable accompanied to all PDIs, increases their correlations more than in the last two Dev. Phases.

All these 1st problem findings suggest that *best*, *worst* and *average non-optimal instability* indicators reflect specific features of someone's cognitive (sub)system activated during repetitive cognitive-motor task solving (except the average performance indicator, which is cumulative indicator that incorporates the rest of three). This conclusion finds support in WPR studies that explain the nature of worst RT in terms of WM and attention mechanisms lapses and in terms of individual differences in neural oscillations (Coyle, 2003; Schmiedek et al, 2007; Unsworth et al, 2010). The evidence also come from neurocognitive studies that explain person's intra-individual variability/instability while performing equivalent RT tasks by neuronal activity source (Booth et al, 2019; Paraskevopoulou et al, 2021; Reed, 1998). Moreover, some researchers proposed cognitive-motor abilities typology based on *best RT performance* (dimension of speed) and *average non-optimal instability performance* (dimension of stability), besides some other PDIs (Drenovac, 2009). Further evidence for specific contribution of

best, *worst* and *average non-optimal instability* indicators to performance dynamics description, comes from the similar research, but with different methodology (Žebec et al, 2014). This research also found that mutual correlations between *best, worst, average performance* and *performance instability* are medium in average, which explains less than 50% of the common factors. Moreover, the same research shows different effects of age and sex on different PDIs, which suggests that various PDIs are variously determined by biological variables. Finally, various effects of Dev. Phase and participant's sex on various PDIs are also proven in this research, within 3rd and 4th Problem's analysis.

Concerning the 2nd Research problem, which deals with age-related change of four PDIs during 8-17 years of age, three findings deserve attention.

First, in all three cognitive-motor tasks all four PDIs improved across the observed ten years long developmental period, and this improvement was non-linear: in the period 8 to 12 years it was several times larger than in the period 12-17 years of age. This finding is expected and in accordance with well-known developmental studies of processing rate development (Cerella & Hale, 1994; Kail & Salthouse, 1994), and inhibition mechanisms development – related primarily to WR-task (Band et al, 2000; Fortenbaugh et al, 2015; Ridderinkhof & van der Molen, 1997). On the other hand, this finding suggest common developmental mechanism for all four PDIs, mostly related to neurological maturation in central part (myelination, synaptic pruning or tuning) and peripheral part (myelination) of nervous system (Hale, Fry & Jessie, 1993; Luna et al, 2004; Travis, 1998, Petanjek et al, 2023), although activated in different developmental periods for different parts of central nervous system.

Second, the intensity of PDIs' relative age-related improvement is different for different PDIs. At one hand, that means that biological variable of age affects differently the combination of neurological resources activated while producing the best or the worst response, or neural bases responsible for performance stability (Booth et al, 2007; Paraskevopoulou et al, 2021; Reed, 1998). On the other hand, age might also affect the strategies of repetitive fast responding via experience with that kind of tasks (which cumulates during childhood and adolescence), and strategies variously affect different PDIs. Namely, there is more "space" for strategy effect in non-optimal instability improvement (produced by responding in all tasks and caused also by distractors and personal variables activated during distractors' inhibition), than in best performance improvement (which appears in only one task, when distractors are absent or minimally present and related personal variables are not needed to activate). The question is whether these differences in relative intensity of age-related improvement (based on two extreme values of PDIs - at the age of 8 years, and at the age of 17 years) are more relevant then ANOVA outcomes of developmental change intensity (which consider not only variability across ages but also within the ages). This will be discussed at 3rd Research problem.

The third important finding at 2nd Research problem analysis reveals possible differences between girls and boys in PDI development. Figures 2a – 2d until 4a - 4d show that red developmental line (girls) at more ages lies below the blue line (boys), which means that in all four PDIs girls tend to attain shorter decision times (DTs) while solving the task and they less deviate from the best DT than boys. This tendency becomes more obvious as cognitive-motor task becomes more complex. Since this tendency is on descriptive level, we will not comment it more, unless we discuss ANOVA tests within the *4th*

Research problem, but on the other analytic scale (Dev. Phases).

One more aspect of possible sex-specific age-related changes of four PDIs provokes curiosity. Namely, the average of PDI's mean changes between all successive ages show that boys' means oscillate more than the girls' means. It might be the consequence of sex differences in sample size at particular age, but quick look at the *Table 1* (age-sex structure of the study's sample) reveals that differences in boys and girls age-related samples' size are not significant. Furthermore, difference in the size of age-related oscillations of PDI's means might be the consequence of sex differences in age-related group variability, so we checked these differences (Levene's test). The conducted variance comparisons revealed that sex differences of results' variances in age-related groups, mostly cannot explain greater boys' oscillations in PDIs' developmental improvement (variances were the same at 82.5 – 95 % comparisons). When we consider that these developmental improvement oscillations in boys appeared at all four PDIs, in all three cognitive-motor tasks, without finding right methodological explanation, we suppose that some developmental mechanism should be responsible for that. The only comparable research available to us shows similar outcome only at analogous performance instability indicator (Žebec et al, 2014).

The analysis of the study results under the scope of the 3rd Research problem was to show whether the developmental improvement in cognitive-motor tasks' performance dynamics is determined by the PDI's type (*best*, *worst*, *average performance*, *average non-optimal instability*), by the complexity of the cognitive-motor task (*SRT, WR, CRT*) and by the sex of the task performer (*girls, boys*).

First, two repeated-measures three-way ANOVA models ([*Dev. Phase*] X [*PDI Type*] X [Participant's *sex*] and [*Dev. Phase*] X [*PDI Type*] X [*Task complexity*]) showed that the developmental improvement was of different intensity for different PDIs. Specifically, across *Dev. Phases*, the average task performance (*cat0*) improves the most, and the average non-optimal instability (*catnof0*) improves the least. Such a finding is not surprising because the *cat0* includes the remaining three PDIs (*ct0min, ct0max* and *catnof0*), and given that these three PDIs improve through *Dev. Phases*, then in the development of the average performance those three improvements are cumulated. Similarly, the weakest developmental improvement of the *catnof0* is also logical. Namely, this instability indicator is largely determined by non-systematic variations in the individual's attention and the non-systematic appearance of distractors, and any independent variable - including the *Dev. Phase* - hardly affects non-systematic variations. Another explanation of the lowest *catnof0* developmental decrement is psychometric. Non-optimal instability (*catnof0*) is calculated as the sum of the differences between two significantly correlated quantities ($DT_i - DT_{min}$, i = 1, 2, 3, …, 30 or 32 number of task items; *DT*= decision time), because they are part of the same person's response time to equivalent cognitive-motor tasks. Since the difference of two correlated variables presents composite variable with reduced reliability, systematic effect of any other variable (e.g. *Dev. Phase*) on low-reliable (composite) variable, *a priori* cannot be large.

Variously intensive developmental improvement of different PDIs with an analogous outcome was observed in the study by Žebec et al. (2014), who used a different reaction meter: the most intensive developmental improvement was noted in *average task performance*, and the least intensive improvement was noted in *performance instability*. Considering that the same finding has been obtained with two different instruments,

with differently sized samples, and on a different developmental scale, it can be reliably concluded that the differentiated developmental improvement of different PDIs is quite firmly proven. Additionally, the study of Dykiert et al. (2012) also observed developmental changes in *average task performance* and in *task performance instability*. With somewhat different data analysis they came to findings that the developmental changes of these two indicators are best fitted by *different* mathematical functions (quadratic and cubic), and that the absolute developmental change is more pronounced in the case of *average performance* than in *performance instability*.

The additional finding obtained under the scope of 3rd Research problem (in our research), which says that the differentiated improvement of different PDIs is more pronounced in the WR-task than in the SRT and CRT tasks, is difficult to comment on because this effect was not found in the literature available to us. We faced the similar situation with the finding that the pattern of differential developmental improvement for different PDIs is different for girls and boys in the SRT and WR cognitive-motor task, but not in the CRT task.

The next specificity of PDIs' developmental changes (found under the scope of the *3rd Research problem*) is their non-equally intensity in three variously complex tasks (*SRT, WR*, *CRT*). Namely, ANOVA showed that each PDI manifests the most pronounced developmental change in the WR task, and the least pronounced change in the CRT task. Such consistency of the task complexity effect on different parts of the intra-individual DT distribution (related to a series of equivalent tasks) indicates that task complexity operates through a certain general mechanism.

An explanation based on a general mechanism involves two inferential premises. The first premise indicates that DT in *elementary cognitive tasks* (ECTs, which contain one to two information-processing stages) decreases nonlinearly with the *ECT-rate* across Dev. Phases. The second premise indicates that total DT in solving more *complex cognitive tasks* (CCTs, which contain more than two information-processing stages) is equal to the sum of DT_is in all *k* information processing stages (i= 1, 2, 3, ..., k). The conclusion of the two premises: the sum of DT_is of all CCT-solving phases will be smaller at an older Dev. Phase than at an earlier Dev. Phase. As a result, differences (DT_{CCT} - DT_{ECT}) in earlier Dev. Phases will be nonlinearly greater than differences (DT_{CCT} - DT_{ECT}) in later Dev. Phases. In other words, DT_{CCT} will decrease across Dev. Phases non-linearly with *CCT-Rate* being greater than *ECT-Rate*.

The hypothesis on general mechanism of the information processing rate development in the human cognitive system was considered by several relevant authors in the field (Cerella & Hale, 1994; Kail & Salthouse, 1994; Miller & Vernon, 1997), although their explanation of this mechanism was partially differently. That hypothesis had its opponents (Cowan et al, 1998; Ridderinkhof and van der Molen, 1997; Madden, Pierce, & Allen, 1993) and apparently, its applicability to development of different measures of information processing rate is not comprehensive. However, it is possible to find childhood research studies that confirmed different rates of RT developmental change in solving variously complex cognitive tasks (Dykiert et al, 2012; Kiselev, Espy, Sheffield, 2009). Additonaly, there are more works that recorded the same phenomenon in the aging period - of course, with the opposite direction of change (Salvia et al, 2016; Gorus, De Raedt and Mets, 2006; Tun & Lachman, 2008). Nevertheless, it looks like general mechanism explanation does not fit to our data. Namely, *3rd Research problem's* ANOVA showed that the *Partial Eta Squared* values are smaller for the

developmental changes of all 4 PDIs in the CRT task than in the SRT task. On the other hand, it is clear that the CRT task is more complex than the SRT task. Therefore, the obtained result of our research probably reflects not only the above-mentioned general mechanism, but also a significantly greater inter-individual variability of the CRT task, than of the SRT task, within Dev. Phases (and this variability reduces the *Partial Eta Squared value*).

The last type of PDIs' developmental changes considered under the scope of *3rd Research problem* was possible sex determination of the developmental improvement in PDIs across the four observed Dev. Phases. The results of *Table 5* and *Table 5.1* showed layered picture of participant's sex effect on PDIs' developmental improvement. When we consider this effect regardless to task complexity (*Table 5*), then the four observed PDIs' developmental changes follow the same pattern for girls and boys (regardless of whether there is a difference between girls and boys at the level of the entire sample). However, when we analyze this sex effect by considering task complexity - i.e. separately for SRT, WR and CRT task (*Table 5.1*) - PDIs' developmental changes partially show different pattern for girls and boys. Specifically, sex differences in *developmental changes* manage to be manifested only in some tasks (SRT, WR) and only in some PDIs (*ct0min, ct0max*), and when they are manifested, they show that the initial developmental advantage of boys disappears in later Dev. phases, or even girls get better. We evaluated these task-specific findings within the context of possible methodological factors' effects (equality of girls' and boys' sample size, equality of girls' and boys' PDIs values' variability, extreme values' effects) and didn't find any methodological source of observed sex differences in PDIs' *developmental changes.*

Therefore, the cause of the rare sex differences in *developmental changes* of the best (*ct0min*) and the worst task performance (*ct0max*) should be sought in some developmental mechanism, and this will be done within discussion of the next (and last) research problem, which is widely related to sex differences in the studied tasks' performance.

Within the scope of the 4th Research problem of this study, we should analyze overall girls' vs boys' differences concerning the cognitive part of performance dynamics while solving the set of equivalent cognitive-motor tasks.

Although the analysis of sex differences in *developmental changes course* revealed that boys in **SRT task** attained higher *best* (*ct0min*) and *worst* (*ct0max*) cognitive performance during the first Dev. Phase, this advantage in the *best performance* disappears during later Dev. Phase. Moreover, in the *worst SRT-performance* girls even over performed boys during the second Dev. Phase (i.e. they showed statistically lower *ct0max*). However, when we observe sex differences in the SRT task cognitive performance over the entire observed period as a whole, *Table 6.1* clearly suggests that the cognitive dynamics of the SRT task performance is in every respect the same in girls and boys. More precisely, boys show statistically insignificant tendency to advantage with the *best cognitive performance*, and girls show same level tendency to advantage with the *worst* and *average cognitive performance*, and with *average non-optimal instability*.

It seems demanding to comment on the obtained findings in relation to previous research because there is very little available research on sex differences in SRT tasks considering cognitive/decision time (DT) in the developmental period of 8-17 years, by using four PDIs.

Regarding the *average cognitive performance* (*cat0*) and *non-optimal cognitive performance instability* (*catnof0*) of the SRT task, in which our study did not find sex differences, only two

comparable studies are available. The study by Eckert and Eichorn (1977) found that boys showed a faster *average cognitive SRT performance* when releasing a key after perceiving a simple visual signal, than girls did. Additionally, the same study did not test sex differences in *performance instability,* although it contained it. On the other hand, the study by Lynn & Ja-Song (1993) did not find differences between 9-years-old girls and boys concerning the *average performance* and *performance instability* of the cognitive part of the SRT task. Nevertheless, there are additional developmental studies of sex differences in *average SRT performance* and *performance instability* that do not separate DT from total RT, which by using total RT confirm a better *average performance* of boys (Dykiert et al, 2012; Ghisletta et al, 2017). However, the same studies show that there are no sex differences in *intra-individual variability (i.e. instability*) of SRT performance in the observed development period. Finally, the absence of sex differences in the best (*ct0min*) and worst (*ct0max*) SRT task cognitive performance from our research we could not compare with any other developmental research on SRT task performance because the aforementioned research did not include those two PDIs.

The picture of sex differences in the performance of the cognitive component of the **CRT task** is somewhat simpler. Namely, the analysis of sex differences in *developmental changes course* in the cognitive performance of the CRT-task found that girls and boys show the same pattern of developmental changes across all four PDI. On the other hand, *Table 6.1* shows that girls, at the level of the entire observed development period, showed better cognitive CRT performance across all four PDI, whereby the advantage in the *best performance* indicator (*ct0min*) did not approach statistical significance. Thus, the pattern of developmental changes of the four cognitive PDIs in girls was systematically shifted to lower values compared to boys, and it can be concluded that the girls' dynamics of the CRT task's cognitive performance in all segments, except for *the best performance*, was superior to the boys' dynamics.

The comparison of this study's findings with the previous researches' findings is again made difficult by the specificity of our research PDIs (only cognitive component of the response was considered, and *the best* and *worst performance* of the CRT task was not used in previous developmental researches). More specifically, the available literature shows that the *average cognitive performance* and the *average instability of the cognitive performance* in CRT task was analyzed only in Lynn and Ya-Song (1993) study. This study reported that 9 years old girls and boys did not differ in terms of the *average performance* and *instability* of the cognitive part of the CRT task. Nevertheless, three additional developmental studies analyzed sex differences in *average performance* and *average instability* of CRT task performance via total RT (rather than just the cognitive part, i.e., DT). Dykiert et al (2012) showed no sex differences in the two PDIs during childhood and adolescence, while Noble, Baker and Jones (1964) showed (1) girls' superiority in the *average CRT tasks performance* from 10 to 13 years of age, and (2) boys' superiority in the rest of the developmental period. The *average instability* of CRT task performance was not investigated in this study. Finally, Žebec et al. (2014) showed that, in the entire developmental period between 8 and 18 years of age, girls show a smaller *average instability* of CRT task performance. However, in terms of *average performance* the picture was more complex: sex differences are not significant throughout the developmental period, while locally girls show better *average performance* at 12, 13 and 16 years of age, and boys at 18 years of age.

The absence of sex differences in *the best CRT task performance*, and the advantage of girls in *the worst CRT task performance* in our study, can be compared with the findings of the study by Žebec et al. (2014). Namely, in that study, boys proved to be more successful in CRT-task *the best performance*, while in regard to *the worst performance*, the picture is more complex: there were no sex differences in the whole observed developmental period, but locally, girls showed better *worst performance* at 12 and 13 years of age, and boys at 10 years of age.

Finally, the analysis of sex differences in *developmental changes course* in the cognitive performance of the **WR-task** revealed the only advantage of girls in *the worst cognitive performance* during the 3rd and 4th Dev. phases (in the previous two phases they were equal to boys). However, when main effect of sex on four PDIs is analyzed at the level of the entire observed development period, then *Table 6.1* shows that, across all four PDIs, the dynamics of girls' cognitive performance is superior (although the smallest advantage was shown for *the best cognitive performance*).

Again, it is difficult to comment on these results in relation to previous studies presented in the literature, because of at least two reasons. More precisely, (1) findings on non-average RT measures (*best performance, worst performance and instability of performance*) are not available to us, and (2) for the *average chronometric performance* of children and adolescents in Go-No Go tasks, only studies using total RT are available, without insight into DT (that we used in our research). The use of total RT includes motor time (MT) in addition to DT, and MT has been consistently shown to be shorter in males of all ages. Therefore, in Go-No Go type RT tasks (that use RT, not DT) boys are given a certain advantage in testing sex differences. In the context of these methodological differences between our and previous research, it should be noted that girls' superiority in the cognitive performance dynamics in WR task, found in our research, is not recorded in the *average RT* of previous research. In particular, research by Clark et al (2006), Gur et al (2012) and Pascualvaca et al (1997) show that boys' *average RT* is shorter than that of girls in the used tasks of the Go-No Go paradigm (in certain periods of the developmental range of 8-17 years). On the other hand, the developmental research of Roalf et al (2014) establishes that there is no sex difference in the *average RT*. However, in all these studies girls showed significantly fewer performance errors.

When the particular images of sex differences in all four PDIs, considered through the SRT, WR and CRT tasks in developmental period 8-17 years, are put together into one whole, we come to general picture of the sex differences in the totality of cognitive performance dynamics (i.e. linear combinations of all four PDIs: *ct0min*, *ct0max*, *cat0* and *catnof0*). This picture indicates that the overall dynamics of *cognitive* performance of three variously simple cognitive-motor tasks, in the developmental period from 8 to 17 years of age, is mostly superior in girls. However, this girls' advantage is least pronounced in the *best cognitive performance* (*ct0min*), and most pronounced in the *worst performance* (*ct0max*), although their advantages in *cat0* and *catnof0* are not significantly less. Finally, this girls' advantage in the dynamics of the cognitive performance systematically increases from the SRT-task to the CRT-task. In other words, the advantage increases with an increase in the working memory load (although the difference between the advantage of girls in the WR-task and the CRT-task is not large), but also with an increase in the proportion of verbal material in the tasks, based on which one should react.

It is possible to offer several explanations for this girls' superiority (in the period of 8-17 years of age)

in the dynamics of the cognitive component of the WR and CRT tasks performance (while there was no difference in the performance dynamics of the SRT task).

The first explanation is the often-mentioned earlier maturation of cognitive functions in girls (Gur et al, 2012; Lynn, Backhoff, Contreras-Niño, 2004; Lynn, Alik, Must, 2000; Pascualvaca, 1997; Roalf et al, 2014; Waber, 1976; Žebec et al, 2014), related to sexual dimorphism in brain development (De Bellis et al., 2001; Lenroot et al., 2007). This maturational difference, especially after girls enter puberty, leads to higher cognitive level of girls than boys of the same chronological age.

Another explanation is related to the verbal character of the WR and CRT tasks, in which the superiority of girls was manifested in the largest scope of performance dynamics (as opposed to the SRT-task, in which the stimulus did not have a verbal character - a series of 6 X's, which are not used in the Croatian language). Given that the females' superiority in perception and manipulation of verbal content is one of the longest-standing findings on sex differences in cognition (Camarata & Woodcock, 2006; Kimura, 1999; Rajchert, Žultak, Smulczyk, 2014; Robinson & Lubienski, 2011; Roivainen, 2011; Waber, 1976), it is expected that the girls will show an advantage in RT test with the verbal stimuli.

The third explanation relates to the fact that in the RT tasks used, the analysis was carried out on the decision time (DT), in which the motor component of the response is negligible, thus neutralizing the systematically proven advantage of boys (Clark et al, 2006; Era et al, 2010; Gur et al, 2012; Lynn & Ja-Song, 1993; Roalf et al, 2014).

Finally, it is possible that the girls' superiority in the cognitive performance dynamics of the WR and CRT tasks was also contributed to by a different task responding strategy, which is discussed in neuroscientific research (Clements-Stephens, Rimrodt and Cutting, 2009) or, in research on greater commitment of the males to greater speed at the expense of accuracy (Ibbotson & Roque-Gutierrez, 2023). Nevertheless, this explanation is difficult to advocate because neuroscientific measurements were not used in the research, and sex differences in the speed-accuracy trade off approach were not recorded.

Conclusions

All previously discussed results of the dynamics of cognitive performance of three variously simple cognitive-motor tasks (which gradually include perception, inhibitory mechanisms of attention and simple working memory processes) show that non-average PDIs justify their introduction into developmental research. The evidence for this come from (1) medium mutual correlations of the four PDIs (whose shared variance indicate PDIs are more unrelated than related), (2) from the fact that PDIs are calculated from different parts of intra-individual RT distribution, related to different neuropsychological processes, and (3) from different effect of sex, developmental phase and task complexity on different PDIs.

The description of *age-related changes* of four PDIs through all 10 years of the observed developmental period (8-17 years) confirms the standard finding on non-linear information processing rate improvement (measured by simple cognitive-motor tasks RT) and therefore the validity of the study. The description suggests superiority of girls over the entire developmental period – increasing from the simplest (SRT) to the most complex (CRT) task – both in terms of shorter decision time, and in less variable developmental improvement compared to boys. These findings are different and original contribution to information processing rate development

research, and based on methodological improvement in "cognitive speed" measurement.

Consideration of the four PDIs' changes *across four developmental phases* of cognitive development (theory of A. Demetriou et al., 2018) showed set of interesting findings. First, these phase-changes are of different intensity at different PDIs, independently of other variables' effects (the most intensive at *average cognitive performance* of the task, and the least at *average non-optimal performance instability*). The explanation of this differentiated PDIs' developmental course at least partly comes from the definition and neuropsychological basis of the four PDIs and the related psychometric consequences. Furthermore, the developmental changes of the four PDIs differed for different cognitive-motor tasks: all four PDIs showed the strongest determination by developmental change in WR-task (cognitive speed + inhibition), and the weakest determination by developmental change in CRT-task (cognitive speed + working memory functioning). Possible explanation of this finding is based on general mechanism of development of all cognitive process phases during the task solving, and on the different inter-individual variability of the three cognitive-motor tasks within the observed developmental phases. Finally, PDIs' developmental changes showed layered relation to the participants' sex. When these changes are considered independent of the task type, they show the same pattern for girls and boys (although this pattern was shifted towards lower decision times in girls, observed over the entire developmental period). However, when PDIs' developmental changes are observed separately for each of the three cognitive-motor tasks, at *average performance* and *non-optimal instability* they kept the same pattern in girls and boys. Nevertheless, PDIs' developmental changes' pattern was somewhat different in girls and boys at the *best* and *the worst performance* in SRT-task and WR-task. This sex differentiation of the *best* and *worst performance* development can possibly be explained by sexual dimorphism in the maturation, which is especially evident when entering puberty (3rd developmental phase).

The sex differences analysis of cognitive performance dynamics in three cognitive-motor tasks, *over the entire observed developmental period*, showed that boys and girls do not differ in the performance dynamics of the SRT-task (cognitive speed with non-verbal stimuli). However, in CRT and WR tasks, girls were superior in terms of all four PDIs, although the least in terms of the *best performance*. This girls' cognitive performance dynamics' superiority in more complex cognitive-motor tasks is explained primarily by girls' earlier maturation, superiority in cognitive processing speed of verbal material (represented in the WR and CRT-task) and by the minimal presence of motor component of the response (in which boys usually show an advantage).

The limitations of the study are primarily related to (1) unequal sample sizes from all age groups of the observed developmental range, (2) sub-optimal reliability of decision time measurements, and (3) the use of verbal material in more complex tests. Therefore, the recommendations for future research would include avoiding these limitations, but also some extensions, in order to clarify results interpretation. In that sense, it would be useful to include motor component of response, within developmental phases' changes and inter-individual variability development in analysis. Moreover, fruitful application of this chronometric aspect of cognitive functioning would be relating its findings with more complex cognitive functions measurement (reasoning, decision making and problem solving).

In conclusion, the findings of the conducted study clearly suggest the use of *non-average indicators* of the cognitive performance dynamics in simple tasks (calculated by decision times, relieved of the motor component of the response). These indicators give layered, broader and partially different picture of ontogenetic development of basic cognitive functions, than the one obtained by analyzing only the *average performance*, measured by total reaction time (RT). This picture becomes even more provocative when the effect of sex and various task complexity are introduced into analysis, since some stereotypes on male's reaction times superiority are questioned.

Acknowledgments

We thank to the Ministry of Education and Sports of Republic of Croatia that supported this research, but also to all the students that diligently participated in the study and all the school staff who patiently adapted to the organizational requirements of the research. Additionally, we thank the assistant researchers who helped in the implementation of the research.

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Appendix 1. Calculation formulas for four performance dynamics indicators

A. minimal RT: *ct0min*= T^0(rank = 1) *(ms)*

B. maximal RT: *ct0max* = T^0(rank = N) *(ms)*

C. mean RT: $cat0 = \frac{1}{N^0} \cdot \sum_{i=1}^{N^0} T_i^0 \ (ms)$

Whereby T_i^0 represents the correct answer in the i-th task of the test, which followed the correct answer of the previous task.

D. mean deviation of response time from best RT: $catnof0 = \frac{ctnof0}{N^0} (ms)$

Whereby *ctnof0* is calculated by formula: $ctnof0 = \sum_{i=1}^{N^0} [T_i^0 - ctfp]$

And *ctfp* means cognitive time of functional potential and is calculated via formula:

$$ctfp = \frac{T^0(rank = 1) + T^0(rank = 2) + T^0(rank = 3)}{3}$$

Here T^0(rank=1. 2. or 3) indicates the time of the first, second, and third shortest correct answer time, which followed the correct answer of the previous task.

IAR Publishing

Journal of Bioanthropology

Volume 4, 2024. p. 77-86

ISSN 2787-8201; UDK 572

https://doi.org/10.54062/jb.4.3.1

Mid-face Morphometrics and Sexual Dimorphism: A Population Specific Study from Southwestern Nigeria

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Received July 25th, 2024
Accepted for publication December 18th, 2024
Online First December 20th, 2024

Keywords: Mid-face, Morphometrics, Sexual Dimorphism Southwestern, Nigeria.

Abstract

This study investigates mid-face morphometrics and sexual dimorphism in a Yoruba population from southwestern Nigeria. A total of 300 participants (112 males, 188 females) aged 16-55 years were examined. Nine mid-facial measurements were taken using standardized anthropometric techniques. Independent samples t-tests revealed significant sexual dimorphism in most variables, with males generally exhibiting larger dimensions. However, nasal height and upper facial height showed no significant differences between sexes. A discriminant function analysis (DFA) was performed to assess the potential for sex determination using these measurements. The DFA model achieved a classification accuracy of 75.3%, with five key variables (left ear width, facial width, nasal width, right ear width, and nasal height) identified as significant discriminators. This accuracy is comparable to similar studies in other populations, suggesting the model's potential utility in forensic applications. The study provides valuable population-specific data on mid-face morphometrics for the Yoruba ethnic group, contributing to the fields of forensic anthropology, plastic surgery, and biometrics. The findings highlight the importance of considering population-specific variations in facial morphology and offer a foundation for future research in facial anthropometry and its applications.

Introduction

The mid-face is the central part of the face that includes the upper lip and lower eyelids. It comprises the maxilla, zygomatic bones, nasal bones, and soft tissues. The maxilla supports teeth and surrounding structures, whereas the zygomatic bones give the midface its distinct shape. The nasal bones keep the nose in shape and provide support for cartilage. The mid-face also includes muscles, fat pads, and skin, which contribute to its appearance and function (Goldstein & Ransom, 2011; Kühnel & Reichert, 2015; Foust et al., 2023; Rao et al., 2023). The mid-face is important from both an aesthetic and functional perspective. Medical specialties, such as plastic surgery, orthodontics, and anthropology, depend on understanding of the mid-face's anatomy (Yaremchuk, 2019, Michelotti et al., 2022, Samizadeh, 2024).

The mid-face plays a crucial role in facial aesthetics due to its central location and substantial impact on overall facial harmony (Narurkar et al., 2016; Londono et al., 2024). It is responsible for several key features that contribute to facial attractiveness, including the position of the eyes, the projection of the cheekbones, and the shape of the nose (Goldstein & Ransom, 2011; Lipko-Godlewska et al., 202; Fillers & Ho, 2023). These features are primarily influenced by the underlying bony structures and soft tissues of the mid-face (Nilendu, 2020).

A well-defined mid-face with prominent cheekbones is frequently associated with attractiveness and is often sought after by individuals pursuing cosmetic enhancements (Linkov et al., 2017; Travieso & Steinbacher, 2019; Fillers & Ho, 2023). The position of the eyes, also located in the mid-face region, significantly influences facial aesthetics. Proper alignment and symmetry of the eyes contribute to a balanced and aesthetically pleasing facial appearance (Reid, 2015; Samizadeh, 2024). The mid-face also exerts a considerable influence on the shape and aesthetics of the nose. The nasal bones, which support the nasal cartilage, play a pivotal role in determining the nose's height and width. This influence of the mid-face on nasal aesthetics is particularly evident in rhinoplasty procedures (Kühnel & Reichert, 2015; Ascha et al., 2018).

Extant literature indicates that the mid-face exhibits sexual dimorphism, with distinct features that differ between sexes. These differences can be attributed to various factors, including hormonal influences and evolutionary adaptations (Kagian et al., 2008; Kreutzer & Aebischer, 2015; Kanavakis et al., 2021; Ridel et al., 2024). The sexual dimorphism in mid-facial structures is a significant aspect of facial aesthetics and plays a crucial role in sex identification. In general, males tend to have a more prominent and angular mid-face compared to females (Beugre et al., 2017; Devanna et al., 2017). This is often characterized by a stronger projection of the cheekbones, a wider and more robust maxilla, and a more prominent brow ridge (Sharma et al., 2014; de Maio, 2015; Avelar et al., 2017; Balaji & Balaji, 2019). On the other hand, females typically have a softer and more rounded mid-face, with less pronounced features (Owsley et al., 2008; Windhager et al., 2011; Corduff et al., 2020). These differences contribute to the perception of facial femininity and masculinity.

The mid-facial region exhibits variations that are specific to populations, shaped by a confluence of genetic, environmental, and evolutionary determinants (Siebert & Swindler, 2002; Cui & Leclercq, 2017; Lacruz et al., 2019). Anthropometry, which entails the systematic quantification and examination of human bodily dimensions, plays a pivotal role in the investigation of these disparities. Through the quantification of mid-facial attributes, scholars are equipped to discern and juxtapose features across distinct geographical locales, thereby facilitating a deeper comprehension of population heterogeneity (Evteev et al., 2014; Evteev et al., 2017; Jilani et al., 2018; Wilke et al., 2023; Utkualp & Ercan, 2015; Dianat et al., 2018; Steckel, 2024). This methodological approach is fundamental to a variety of disciplines, including orthodontics (Guo et al., 2012), plastic surgery (Afaq et al., 2023), anthropology (Johnson et al., 2023; Thakur & Sehrawat, 2023), sleep medicine (Chen et al., 2022, 2023), prosthodontics (Ariani et al., 2013), and biometrics (Wilkinson, 2015), where accurate measurements are instrumental in informing treatment protocols and augmenting scientific knowledge.

Mid-face anthropometry plays a crucial role across medical and scientific disciplines, yet comprehensive morphometric data remain scarce for many populations, including Southwestern Nigeria. This study aims to fill this gap by establishing baseline mid-face measurements for this population. The data will enrich knowledge of population-specific facial morphology and support applications in orthodontics, plastic surgery, anthropology, sleep medicine, prosthodontics, and biometrics, enhancing accuracy in procedures and advancing understanding of facial diversity.

Materials and methods

Study Design/ Sample

This prospective cross-sectional study was carried out on 300 students (112 males and 188 females) of the University of Medical Sciences, Ondo state, Nigeria within the age range of 16 - 55 took part in the study. The study participants are all the students and staff of the University of Medical Sciences Ondo State belonging to the Yoruba ethnic group of Nigeria.

Anthropometric Data Collection

A semi-structured questionnaire was developed for the study and administered to the participants for the purpose of collecting socio-demographic data. Direct measurements were carried out on each participant after the reception of a signed informed consent letter.

Eight craniofacial variables were measured on each subject. Measurements were taken in accordance with the methods suggested by Martin and Saller, (1957).

Upper Facial Height (UFH): Upper facial height is the measurement of the face from the Glabella to Subnasale.

Nasal Height (NH): Nasal height is the measurement of the face from the Nasion to Subnasale.

Nasal Width (NW): Nasal width is the measurement of the face to determine the distance between two alare to alare.

Facial Width (FW): Facial width is the measurement of the face to determine the distance between two zygon.

Ear Length (EL): Ear length is the measurement of the ear from superaurale to subaurale.

Ear Width (EW): Ear width is the measurement of the ear from preaurale to postaurale.

Inner-Canthal Distance (ICD): Inner-canthal distance is measurement of the eye from the medial canthus of one eye to the medial canthus of the other eye.

Outer-Canthal Distance (OCD): Outer-canthal distance is the measurement of the lateral angle of the left eye to the lateral angle of the right eye.

Equipment

These variables were measured with a spreading caliper (Biotech Ltd., Agra, India) and digital vernier caliper (Microtech, Ukraine, precision, ± 0.01 mm).

Statistics

Data analysis was carried out using Microsoft excel 2019 and Statistical Package for the Social Sciences (IBM® SPSS version 25.0, Armonk, New York, USA). The significance criterion was set at 95%; hence p 0.05 was significant. Continuous variables were expressed as Means SD (standard deviation). Sex differences were established using the independent sample t-test and stepwise discriminant function analysis (DFA) was used to quantify sexual dimorphism using variables that significantly contributed to mid facial variability. Leave-One-Out Cross-Validation was employed to avoid over fitting of the DFA model.

Ethical considerations

Ethical approval was obtained from the Research Ethics Committee at the University of Medical Science, Ondo, Nigeria with ethical approval number: NHREC/TR/UNIMED-HREC- Ondo St/22/06/21. Informed consent forms were provided to the volunteers or their guardians for those below 18years of age; and those who consented and satisfied the inclusion criteria were invited for the study. Individuals were deemed unsuitable for the study if their parents, up to the second filial generation, were not of the Yoruba ethnic group of southwestern Nigeria, if they presented with visible craniofacial or skeletal dysmorphology, or if they exhibited obvious signs of metabolic diseases such as obesity.

Results

Table 1 presents descriptive statistics and independent samples t-test results for various midface variables, comparing measurements between male (n = 112) and female (n = 188) participants. The variables analyzed include inner canthal distance (ICD), outer canthal distance (OCD), right ear length (REL), right ear width (REW), left ear width (LEW), nasal height (NH), nasal width (NW), facial width (FW), and upper facial height (UFH).

Statistically significant differences ($p < .05$) between males and females were observed for most variables, with males generally exhibiting larger measurements. However, no significant differences were found for nasal height ($p = 0.351$) and upper facial height ($p = 0.574$). These results suggest the presence of sexual dimorphism in several midface features among the study participants.

Table 1: Descriptive and inferential statistics of mid-face variables amongst study participants

Variables	Sex	N	Mean±SD	t	df	P-value
ICD (mm)	M	112	36.60±3.34	3.108	298	0.002*
	F	188	35.37±3.32			
OCD (cm)	M	112	14.13±0.89	5.409	298	<0.001*
	F	188	13.48±1.07			
REL (mm)	M	112	55.79±3.72	4.576	298	<0.001*
	F	188	53.83±3.52			
REW (mm)	M	112	32.32±2.71	7.336	298	<0.001*
	F	188	29.96±2.70			
LEW (mm)	M	112	31.34±2.23	7.625	298	<0.001*
	F	188	29.16±2.48			
NH(mm)	M	112	52.58±4.80	-0.935	298	0.351
	F	188	53.09±4.46			
NW (mm)	M	112	32.62±4.51	5.877	298	<0.001*
	F	188	29.39±4.67			
FW (mm)	M	112	146.61±8.52	5.331	298	<0.001*
	F	188	139.97±11.41			
UFH (mm)	M	112	60.57±4.92	0.563	298	0.574
	F	188	60.26±4.39			

Note. ICD = Inner Canthal Distance; OCD = Outer Canthal Distance; REL = Right Ear Length; REW = Right Ear Width; LEW = Left Ear Width; NH = Nasal Height; NW = Nasal Width; FW = Facial Width; UFH = Upper Facial Height. Values for Male and Female columns are presented as Mean ± Standard Deviation, * = significant.

Discriminant analysis

Table 2: Variables contributing to the stepwise discriminant function analysis

			Exact F			
		Lambda	Statistic	df1	df2	Sig.
Step	Variables					
1	LEW (mm)	0.837	58.142	1	298.00	<0.001
2	FW (mm)	0.783	41.234	2	297.00	<0.001
3	NW (mm)	0.744	34.039	3	296.00	<0.001
4	REW (mm)	0.730	27.346	4	295.00	<0.001
5	NH(mm)	0.719	23.022	5	294.00	<0.001

Note. Lambda = Wilks' Lambda; df = degrees of freedom; Sig. = significance level. Variables are listed in the order they were entered into the model. Minimum F to enter = 3.84; Maximum F to enter = 2.71.

Table 3: Discriminant function analysis for craniofacial variables

Variables (mm)	Standardized coefficients	Unstandardized coefficients	Eigen Value	Canonical Correlation	Wilks' Lambda	Chi-Square Sig
REW	0.344	0.128	0.392[a]	0.530	0.719	<0.001
LEW	0.413	0.173				
NH	-0.234	-0.051				
NW	0.420	0.091				
FW	0.458	0.044				
Constant	-	-15.462				

Note. REW = Right Ear Width; LEW = Left Ear Width; NH = Nasal Height; NW = Nasal Width; FW = Facial Width. All measurements are in millimeters (mm).

The eigenvalue of 0.392 indicates moderate discriminating power. The canonical correlation of 0.530 suggests a moderate relationship between the discriminant scores and group membership. The Wilks' Lambda value of 0.719 indicates that 28.1% (1 - 0.719) of the variance in the dependent variable is explained by group differences. The significant chi-square value (p□0.001) confirms that the function significantly differentiates between the groups. The standardized coefficients indicate the relative contribution of each variable to the discriminant function. Positive coefficients contribute positively to group discrimination, while negative coefficients contribute negatively. These coefficients can be used to construct the discriminant function equation for classifying new cases. Additionally, unstandardized coefficients can be used for this purpose.

Table 4: Functions at the group centroids depicting average discriminant scores in males and females

Sex	Function	Sectioning point
	1	
M	0.808	0.164
F	-0.481	

Note. Unstandardized canonical discriminant functions evaluated at group means. The sectioning point (0.164) represents the midpoint between group centroids.

Positive values are associated with male cohorts, and negative values are associated with group female cohorts; or scores above the sectioning point are most likely males, and scores below the sectioning points are most likely female.

Table 5: Classification accuracy of the functions in stepwise discriminant function analysis

		Sex	Predicted Group Membership		Total
			M	F	
Original	Count	M	88	24	112
		F	50	138	188
	%	M	**78.6**	21.4	100.0
		F	26.6	**73.4**	100.0
Cross-validated[b]	Count	M	85	27	112
		F	53	135	188
	%	M	**75.9**	24.1	100.0
		F	28.2	**71.8**	100.0

Note. M = Male; F = Female. Original classification results are based on the analysis sample. Cross-validated classification is produced by leaving out each case one at a time and then classifying that case based on the functions derived from all other cases.

The findings from the stepwise discriminant function analysis reveal notable classification accuracy in predicting sex based on mid-face measurements. In the original analysis, 78.6% of males and 73.4% of females were correctly classified. Cross-validation yielded slightly lower accuracy, with 75.9% for males and 71.8% for females.

Discussion

This study examined sexual dimorphism in the mid-face among 300 individuals (112 males, 188 females) from the Yoruba ethnic group of southwestern Nigeria. Our findings revealed significant sexual differences in most of the examined variables, highlighting the importance of considering sex-specific variations in facial morphology. Additionally, we identified specific mid-face measurements that exhibited the most pronounced differences between males and females, shedding light on potential markers for sexual dimorphism in the study population.

The results of our independent samples t-tests (Table 1) demonstrate significant sexual dimorphism in the

majority of mid-face variables examined. Males consistently exhibited larger measurements than females in inner canthal distance (ICD), outer canthal distance (OCD), right ear length (REL), right and left ear width (REW, LEW), nasal width (NW), and facial width (FW). These findings align with previous studies that have reported larger craniofacial dimensions in males compared to females (Agnihotri et al., 2011; Jilani et al., 2018; Cappella et al., 2020; Hodges-Simeon et al., 2021; Velemínská et al., 2012; Herrerín & Carmenate, 2022; Toneva et al., 2022; Christy et al., 2023; Goli et al., 2023; Syutkina et al., 2023). The observed variations between male and female mid-facial measurements, as shown in the study findings, likely stem from a mix of inherited traits (Devanna et al., 2020; Vishwakarma et al., 2024), hormone influences (Roosenboom et al., 2018), and external environmental elements (Delwing et al., 2012; Syutkina et al., 2023).

Interestingly, no significant differences were found between sexes in nasal height (NH) or upper facial height (UFH). This lack of dimorphism in vertical facial measurements implies that sexual differences in the midface region are more noticeable in horizontal dimensions. This finding has been reported in several previous population-based studies, including Anand et al. (2015) among Indians in the Moradabad population, Kramer et al. (2012) in white Europeans, Diouf et al. (2014) in young adults from Pakistan, Hierl et al. (2021) in a Caucasian population, Danel et al. (2018) in Brazilian, Colombian, Cameroonian, and Czech populations, and Syutkina et al. (2023) in an East Slavonic population. The data derived from this study could have an impact on facial reconstruction techniques and inform aesthetic considerations in facial surgery.

Sexual dimorphism is crucial in forensic anthropology. It plays a significant role in identifying the biological sex of human skeletal remains, which is essential for establishing the identity of unknown individuals in forensic investigations (Lestrel et al., 2011; Sagana & Mohanraj, 2019; Boucherie et al., 2022). This study carried out a stepwise discriminant function analysis (DFA) of the mid-facial variables to identify those that sufficiently discriminate sex within the population. The model successfully classified 75.3% of the original cases and 73.3% of the cross-validated cases, indicating good predictive accuracy. Five key variables (left ear width, facial width, nasal width, right ear width, and nasal height) were identified as significant discriminators between sexes. The upper facial height, however, did not contribute significantly to sex discrimination ($p=0.574$).

Our DFA model's 75.3% classification accuracy is in line with results from other populations. Sarkar and Mukhopadhyay obtained 68.5% accuracy in a population of east India, while Ali et al. reported 74.5% accuracy in Brokpas & Purigpas of Ladakh. Adamu et al. found a 70.3% accuracy rate in the Hausa population of Kano state, Nigeria. In a Brazilian population, Capp et al. reported 82-90% accuracy. Sezgin and Karadayi reported 80.5% accuracy in a Turkish population, and Marinescu et al. reported 83.5% accuracy in a Romanian population. These comparisons indicate that our model's performance falls within the range of previously published studies, with minor variations that may be attributed to population-specific characteristics.

While the present study offers significant contributions to the understanding of sexual dimorphism and mid-face morphometrics within the Yoruba demographic of southwestern Nigeria, it is imperative to recognize several inherent limitations. Initially, the research was restricted to a singular ethnic cohort, which may constrain the applicability of the results to alternative populations or ethnicities. Furthermore, although the sample size was deemed sufficient for the scope of this study, augmenting it in subsequent inquiries could enhance both statistical power and the reliability of the findings. Moreover, the dependence on manual anthropometric assessments introduces a potential for observer bias, notwithstanding efforts aimed at standardizing the methodologies for data collection.

Future research endeavours could effectively mitigate these limitations by incorporating a more heterogeneous array of populations to investigate inter-ethnic and cross-regional disparities in mid-face morphometrics. Additionally, the utilization of advanced imaging modalities such as 3D scanning or cone-beam computed tomography (CBCT) could

significantly refine the accuracy of measurements and diminish the likelihood of observer bias. Longitudinal investigations that assess variations in mid-face morphology over time, in conjunction with age and environmental influences, could yield profound insights into the dynamics of craniofacial architecture. Lastly, the integration of genetic and hormonal data may elucidate the fundamental factors that underlie sexual dimorphism in mid-face structures, thereby furthering applications in forensic and medical fields.

Conclusion

This study investigates sexual dimorphism and mid-face morphometrics in a Yoruba population in southwest Nigeria. Mid-facial measurements show significant sexual dimorphism, with males typically having larger dimensions than females. The discriminant function analysis model achieved a classification accuracy of 75.3%, providing a targeted set of measurements for future use in forensic anthropology and related disciplines. Five key variables were found to be significant discriminators between the sexes: left ear width, facial width, nasal width, right ear width, and nasal height. Interestingly, nasal height and upper facial height did not exhibit any discernible sexual dimorphism, suggesting that vertical facial dimensions may be less sexually dimorphic in this population. The generated population-specific data has implications for forensic applications, plastic and reconstructive surgery, anthropological research, and biometric applications.

Acknowledgments

We sincerely appreciate the study participants for taking time out to participate in our study.

Financial disclosure and conflict of interest

The authors assert that they have no conflict of interest to declare. We did not receive any funding for this study.

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IAR Publishing

Journal of Bioanthropology

Volume 4, 2024. p. 87-95

ISSN 2787-8201; UDK 572

https://doi.org/ 10.54062/jb.4.3.6

Assessment of Plantar Arch Index and Prevalence of Flat Foot Among Adult Ikwerre Residing in Port Harcourt, Rivers State

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Received January 27th, 2025
Accepted for publication June 13th, 2025
Online First July 7th, 2025

Keywords: Flat foot, Plantar Arch Index (PAI), Footprint, Ikwerre.

Abstract

Feet abnormality such as flat foot resulting from the collapse of the arches of the foot is of great clinical and anatomical importance. This study aimed to assess the plantar arch index and determine the prevalence of flat foot among adult Ikwerre residing in Port Harcourt, Rivers State Nigeria. A total of 100 subjects consisting of 50 males and 50 females were recruited for this study. The bilateral footprints of the subjects were obtained using stamping ink and A4 plain papers. Convenience sampling technique was used in collecting samples. Data were analyzed using statistical package for social science (SPSS version 23) and Microsoft Office Excel 2019. Staheli's plantar arch index method was adopted and the presence of flat foot was identified from the data collected by calculating the plantar arch index (PAI). If the value of PAI is >1.15, it is considered as flat foot. The result showed that the right plantar arch index of male participants was significantly higher than that of the left. About 4% flat foot on the right feet and 6%flat foot on the left feet were observed in males while no flat foot was recorded in right foot and 10% flat foot on the left foot were recorded in females. The findings in the study suggest a higher prevalence of flat feet in left foot than the right foot with females having higher rate of left flat foot than the males.

Introduction

The term flat foot is commonly used to describe a nebulous mixture of anatomical variations as well as a small core of pathological conditions (Rose et al., 1985; Igbigbi et al., 2002; Pranati et al., 2017; Akinlolu et al., 2021). Flat feet or pes planus is a postural deformity in which the arches of the foot collapses, with the entire sole of the foot coming into complete or near-complete contact with the ground. There is a functional relationship between the structure of the arch of the foot and the biomechanics of the lower leg. The arch provides an elastic, springy connection between the forefoot and the hind foot. This association safeguards the body such that a majority of the forces incurred during weight bearing of the foot can be dissipated before the force reaches the long bones of the leg and thigh (Franco, 1987).

Flat feet, also known as acquired flat foot disorder, result from collapsed arch. When standing, the sole of the foot should not touch the ground completely. However, a fallen arch causes the foot to roll inwards and the entire sole comes close to touching the ground. The feet are fundamental to the mobility of the body, flat feet can cause problems throughout the skeletal

structure and can even bring the joints out of alignment (Donatelli et al., 2024).

In pes planus, the head of the talus bone is displaced medially and distal from the navicular. As a result, the spring ligament and the tendon of the tibialis posterior muscle are stretched, so much so that the individual with pes planus loses the function of the medial longitudinal arch (MLA). If the MLA is absent or non-functional in both the seated and standing positions, the individual has rigid flatfoot. If the MLA is present and functional while the individual is sitting or standing up on their toes, but this arch disappears when assuming a foot-flat stance, the individual has supple / flexible flatfoot. This latter condition can be correctable with well-fitting arch supports (Snell, 2012; Hayley et al., 2017; Rithanya et al., 2018).

The appearance of flat feet is normal and common in infants, partly due to "baby fat" which masks the developing arch and partly because the arch has not yet fully developed. The human arch develops in infancy and early childhood as part of normal muscle, tendon, ligament and bone growth (Pina-Diaz et al., 2024). Training of the feet, especially by foot gymnastics and going barefoot on varying terrain, can facilitate the formation of arches during childhood, with a developed arch occurring for most by the age of four to six years. Flat arches in children usually become proper arches and high arches while the child progresses through adolescence and into adulthood (Umar and Tafida, 2013; Gregory, 2020; Solanki et al., 2020).

The arch of the foot demonstrates two extremes of anatomical structural position the high arch characteristic of the pes cavus and the flat arch the pes planus. Although there are three distinct arches whose function is to support the foot, the medial longitudinal arch (MLA) has been found to be the arch of clinical significance. Problems and mal-alignments originating involving the MLA ultimately affect the functioning of the muscles and joints of the ankle, knee, hip, and low back, all of which depend on the base of support provided by the MLA (Karataş & Karasu 2024).

The prevalence of pes planus declines with age, being higher in children with ligament laxity and early shoe wearing which impairs longitudinal arch development (Hernandez et al., 2007; Gianmarco et al.,2015; Gavin et al.,2020). The lower limb, and particularly the foot, is amongst the most distinctive characteristics of human anatomy (Hernandez et al., 2007). Footprint of hominoids already demonstrated the existence of plantar arch 3.7 million years ago (Hernandez et al., 2007). The orthopaedic examination served to recognize disorders that are known to change feet consistency. The identification of congenital problems, particularly involving the feet; postural abnormalities of the spine, pelvis, hips, knees, Achilles Tendon shortening, and restraint to subtalar joint movements are essential for ruling out the possibility of secondary pes planus. (Hernandez et al., 2007; Chiamayee et al.,2020; Samuel &Tun,2020; Sergey et al.,2020).

The medial longitudinal arch of the foot is of great importance because it helps protect the foot from injuries (Yalfani et al., 2024). It is an important highly variable structure characteristics of the human foot which provides necessary shock absorption for the foot during activities. Traditionally, feet are classified as being high, normal or low arched. A high arched foot is supposed to be at increased risk of injuries to the bony structures on the lateral aspect of the foot (over-supinated), whereas a low arched foot can be at greater risk for soft tissue damage on the medial part of the foot (over pronated) (Gehlen & Märdian, 2024).

In Europe and America flat foot is a common reason for attendance at a children's orthopaedic clinic, but in India and most low-income countries, children are seldom brought for treatment for flat foot (Rao et al., 1992). This shows that there is lack of awareness about flat foot among the uneducated and economically backward people.

Materials and methods

This study was conducted on adult subjects (18-40) from Ikwerre ethnic group residing in Port Harcourt. A total of hundred (100) Adult subjects, fifty (50) male and fifty (50) who met the inclusion criteria were randomly selected. Their footprint was obtained by instructing the subject to place the foot in a mode which contained a rectangular piece of foam of the mode size.

The foam was wet with ink, the foot was then placed on a clean A4 paper placed on a flat smooth surface. After the plantar surface was printed on the paper, the subject was asked to raise his/her leg while cotton wool soaked in methylated spirit was used to wipe the stained ink on the plantar surface. The same procedure was repeated for the both feet.

The plantar arch index (PAI) of each foot was obtained according to Staheli's method. For calculating PAI, a tangential line was drawn connecting the edge of the medial forefoot and heel region. The mid-point of this straight line was calculated by dividing the full length by half. From this marked point, a perpendicular line was drawn crossing the footprint (Figure 1). The same procedure was repeated at the heel region for heel tangency point. The width of the central region of the footprint was considered as 'A' and that of the heel region is considered as 'B'. All measurements were taken in centimeters (cm). Plantar arch index (PAI) was obtained by dividing the A value by B value (Hernandez et al., 2007). Plantar arch index (PAI) = A/B. PAI greater than 1.15 was considered as flat foot.

Figure 1: Foot print of subject

The subjects were randomly selected. Sample size determination was done using Cochran's formula for population infinite or large population and the sample size used for this study was 100.

Figure 2: Foot print showing how measurements were derived

Mathematically, it is represented as:

$$\frac{z^2pq}{d^2}$$

Sample Proportion=Total Research Population/Total Nigeria Population

Results

Table 1 shows the summary of all measured foot parameters in both right and left. The right and left foot of all study participant had approximately the same length (24.54cm). The right width, A and B were slightly more in the right foot than in the left foot.

The Table 2 shows the comparison of the left plantar indexes with the right plantar arch indexes. The left foot had slightly higher plantar arch index, however this difference was not significant (t=1.093; p-value=0.227).

Table 1: Descriptive statistics of measured foot parameters of all subjects in the study

Foot parameter (cm)	Mean ± SEM (N = 100)	SD	Min	Max
Right Foot				
Length	24.54 ± 0.14	1.43	21.5	27.5
Width	8.99 ± 0.05	0.52	8.0	10.5
A	4.42 ± 0.14	1.37	2.0	8.5
B	5.33 ± 0.08	0.75	4.4	7.6
Left Foot				
Length	24.54 ± 0.14	1.44	21.5	27.8
Width	8.90 ± 0.05	0.54	7.5	10.5
A	4.29 ± 0.12	1.23	2.5	8.0
B	5.20 ± 0.07	0.72	3.9	7.3

Table 2: Plantar index of right and left feet of all subjects of the study

	Right foot	Left foot
Mean	0.81	0.82
SEM	0.01	0.02
SD	0.18	0.20
Min.	0.44	0.48
Max.	1.27	1.33

t = 1.093; p-value = 0.227

Table 3: Comparison of right foot parameters of participants based on gender

	Male (N=50)		Female (N=50)			
Parameters (cm)	**Mean ± SEM**	**SD**	**Mean ± SEM**	**SD**	**t-test**	**p-value**
Length	25.43 ± 0.17	1.21	23.65 ± 0.15	1.04	7.837	0.001*
Width	9.30 ±0.06	0.45	8.70 ± 0.05	0.38	7.215	0.001*
A	4.70 ± 0.18	1.30	4.15 ± 0.20	1.40	2.044	0.044*
B	5.48 ± 0.10	0.74	5.19 ± 0.11	0.75	1.967	0.052*
PI	0.85 ± 0.03	0.19	0.76 ± 0.02	0.16	2.536	0.013*

Table 3 shows the comparison of the right foot parameters based on gender. The male right foot length was significantly higher than the female length (25.43cm as against 23.65cm). The width and the Plantar Index was also higher in males when compared to females (p=0.001 and p=0.013 respectively).

The result shown in table 4 displays the comparison between the left foot parameters in the male and female gender. The male foot length and width were significantly higher than females (p=0.001 and p=0.001). On the left feet the plantar arch index of males was higher (0.83) than that of females (0.81) though the difference was not significant.

Table 4: Comparison of left foot parameters of participants based on gender

Parameters (cm)	Male (N=50) Mean ± SEM	SD	Female (N=50) Mean ± SEM	SD	t-test	p-value
Length	25.49 ± 0.16	1.11	23.60 ± 0.15	1.06	8.699	0.001*
Width	9.16 ± 0.06	0.45	8.62 ± 0.07	0.48	5.882	0.001*
A	4.42 ± 0.16	1.16	4.16 ± 0.18	1.28	1.094	0.277
B	5.35 ± 0.12	0.77	5.04 ± 0.09	0.64	2.165	0.033*
PI	0.83 ± 0.03	1.19	0.81 ± 0.03	0.21	0.311	0.756

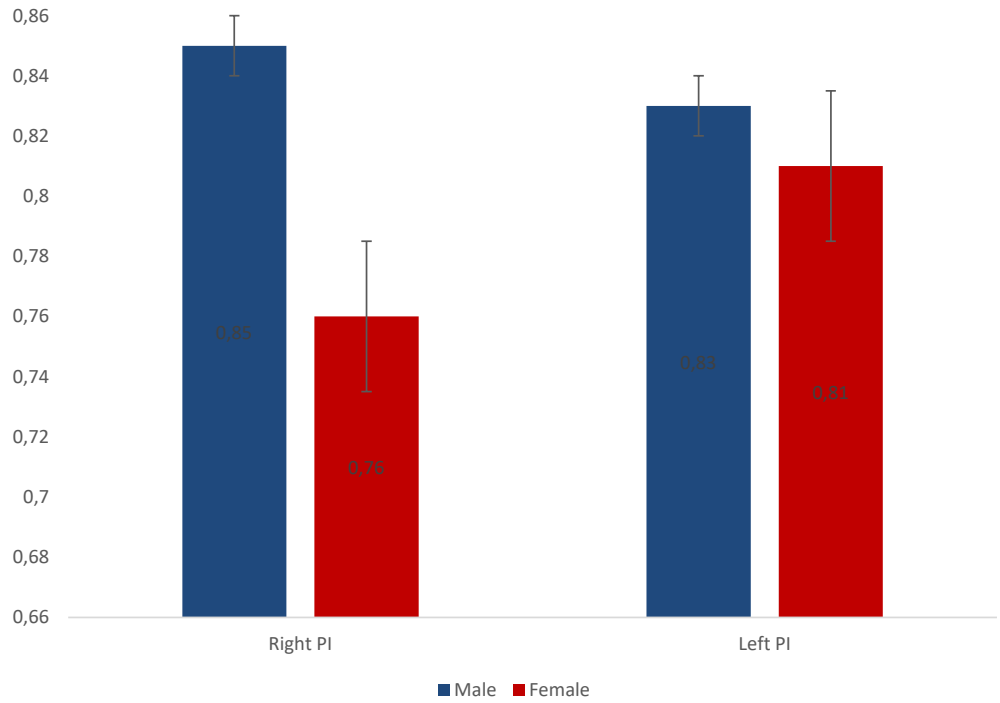

Figure 3: Bar chart showing average plantar arch index of both feet based on gender of the participants

Table 5: Plantar index classification of both feet of participants

	Frequency (n)	Percentage (%)
Right feet		
≤ 1.15 (Normal)	98	98.0
> 1.15	2	2.0
Left feet		
≤ 1.15 (Normal)	92	92.0
> 1.15	8	8.0

The table above displays the plantar arch index classification in both left and right foot of study participants. About 98% of study participants had a right plantar arch index that were normal (≤ 1.15) while about 2% of the subjects indicated abnormality in right plantar arch index (>1.15). The left foot plantar arch index of subjects indicated 8 abnormalities.

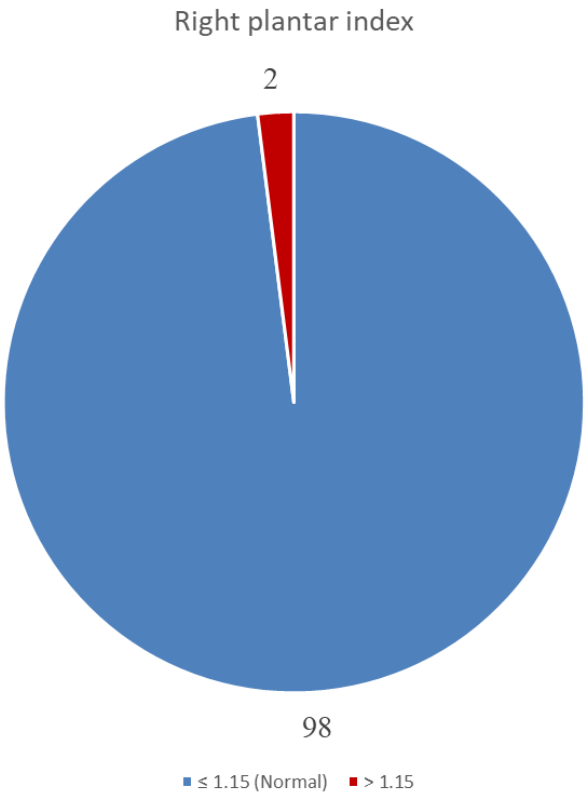

Figure 4: Pie chart showing proportion of participants with normal Right plantar arch index (normal PI ≤ 1.15).

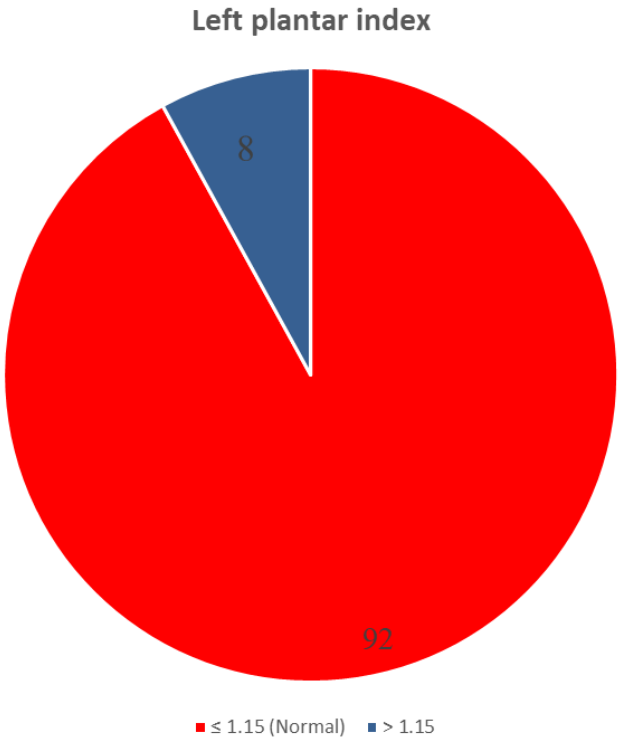

Figure 5: Pie chart showing proportion of participants with normal left plantar arch index (normal PI ≤ 1.15)

Table 6: Comparison of plantar index class among male and female participants in the study

Variable	Gender		Total	Chi square	p-value
	Male n (%)	Female n (%)			
Right PI					
≤ 1.15	48 (96.0)	50 (100.0)	98 (98.0)	2.041	0.495
> 1.15	2 (4.0)	0 (0.0)	2 (2.0)		
Left PI					
≤ 1.15	47 (94.0)	45 (90.0)	92 (92.0)	0.543	0.715
> 1.15	3 (6.0)	5 (10.0)	8 (8.0)		

Table 6 shows comparison of plantar index classification among male and female participants in the study. From the results 96% of males had normal right plantar index while 4% had higher than normal plantar index. All females had right plantar indexes that was normal. From the left 94% of males and 90% of females had normal left plantar arch index while 6% males and 10% of the female population had left plantar arch index higher than 1.15

Discussion

The human foot being an essential tool for motion is highly essential in bipedal species since any deformity in it could have far reaching consequences on the quality of life of the patient. High foot arches are associated with various musculoskeletal instability necessitating orthopedic intervention (Adler, 2024). Low foot arches also known as flat foot has been associated with gait abnormality and even spine deformity (Abbasi et al., 2024). Understanding the prevalences as well as foot parameters of the study population will aid clinicians as well as forensic scientists in taking informed decisions. In this, there was a significant difference in all measured right foot parameters of the study, when compared between males and females (length, width, plantar index). The male participants had higher values of all parameters ($p<0.05$) when compared with the females and this is likely due to some anatomical variations that exists between males and females. This may indicate that foot parameters exhibits sexual dimorphism in the study population. On the other hand, the left foot parameters showed significant difference only in length, width and A parameters between males and females.

Plantar index was higher in left feet of males than females although the difference was not statistically significant. The right plantar index of males in the study was slightly higher than that females; mean plantar arch index. The result show that the plantar arch index was determined to be 0.81 for the right foot and 0.82 for left foot, in the combined males and females.

There was a slight difference in mean value of the plantar arch index of the left and right feet as left foot had higher value (0.82) against right foot (0.81). Similarly, minor difference was noticed in value of the right and left foot width of the participants as right foot width stood at 8.99cm against left foot of 8.91cm value.

The prevalence of flat foot is low as only 8% of the participants have left flat foot while 2% of the participants have right and 92% of the participants have normal left foot and 98% have normal right foot. The result also reveal that flat foot can occur unilaterally or bilaterally. Also, this study reveals the males bilaterally have higher plantar arch index, foot length and foot width than females. Following the result of this study, it shows that males have more flat foot deformity compare to the females. This can be attributed to the out-door activities that many males are involved in.

The low level of prevalence in flat foot among Ikwerre adults residing in Port Harcourt can be attributed to their life style since the participants were engaged in little or no farming activities, less walking compared to rural dwellers. There is proper medical attention in city and proper medical facilities in case foot or ankle injuries, proper medical management of Rheumatoid arthritis which is one of the leading causes of flat foot. There is also proper surgical intervention in case of rupture of the posterior tibial tendon

It is also important to note that flat foot can be inherited (Yang and He, 2024) as some of the participants came from families where the gene of flat foot is dominant while some the participants acquired flat foot as a result of being athletic.

Conclusions

From this study, it can be deduced that the plantar arch index (PAI) of adult Ikwerre residing in Port Harcourt is 0.81 for the right and 0.82 for the left foot while the foot length is 24.54cm for the both foot and 8.99cm for right width and 8.90cm for the left foot width. It can also be deduced that prevalence of flatfoot among adult Ikwerre residing in Port Harcourt is very low.

Acknowledgements

Special acknowledgement to the participants for their cooperation in making the research a success.

Conflicts of interest

All authors declare that there is no form of competing interests.

Authors' contribution

GSO was the lead researcher, designed the protocol, performed statistical analysis and wrote first draft. GOB, PC, BM and BKA participated in the writing of the first draft. NIO carried out the data collection and

statistical analysis. All authors discussed the results and agreed to submit the final manuscript for publication

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IAR Publishing

Journal of Bioanthropology

Volume 4, 2024. p. 96-105

ISSN 2787-8201; UDK 572

https://doi.org/10.54062/jb.4.3.2

Consanguinity in twenty-first century India: A review

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Received August 16th, 2024
Accepted for publication December 20th, 2024
Online First December 22nd, 2024

Keywords: Consanguinity, Factors, Disorders, Reproductive Outcome, Change, India.

Abstract

Consanguineous marriage, which involves the union of close biological relatives, is a global practice, including in India. Consanguineous marriage and its effect remained an interest to the geneticists, medical and social scientists. Numerous studies have been conducted to delve into these aspects of consanguinity. This review paper seeks to examine various dimensions of consanguinity in twenty-first-century India. We conducted thorough searches on PUBMED, Web of Knowledge, Google Scholar, and JSTOR specifically for articles on consanguinity in India since 2001. It was observed that the rate of consanguinity was approximately 10.0% which varies state-wise, and the trend indicates a decrease. Socio-demographic characteristics such as age at marriage, educational attainments, place of residence, and economic condition are the major contributing factors. Religious beliefs, especially Islamic views, significantly affect the prevalence of consanguineous marriage. Many studies reveal that consanguinity helps to lower dowry, maintain family peace, and increase social security within groups. Recent studies reveal that consanguinity still affects reproductive outcomes and increases congenital and medical disorders, while the inclusion of external factors reduces the effect of consanguinity. Studies show consanguinity reduces the overall strength of a population and increases the selection pressure within it. This review helps in understanding the effects of consanguinity among concerned couples and family members and encourages policymakers to motivate them to seek genetic counselling for a better future.

Introduction

Consanguineous marriage is an important social phenomenon, and is found to be very important to the geneticists, medical and social scientists because of its effect on reproductive behaviour, congenital malformations, medical disorder, health problems among newborn babies as well as social importance (Banerjee & Roy, 2002; Bittles & Black, 2010; Amudha et al. 2005; McGregor et al. 2010; Ashraf et al. 2010). Several studies have been conducted to gain insight into family relations in consanguineous marriages and attitudes and intergenerational changes in consanguinity (Mukherjee et al. 2007; Kalam et al. 2017). This study aims to present a detailed review of consanguineous marriage in twenty first century India.

Definition

Consanguineous marriage is the marriage between biological relatives, having at least one common ancestor (Bittles, 2012). It can be categorized by the degree of relationship between spouses such as first cousins paternal or maternal side, second cousins, third cousins, uncle–niece or distant relations (Bittles, 2012).

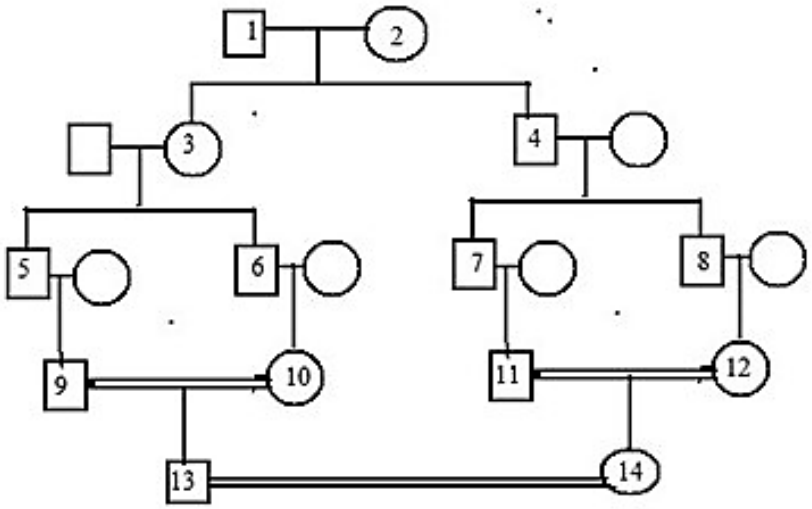

Figure 1: Common ancestors of each consanguineous couple

Methods

We conducted rigours search on PUBMED, Web of Knowledge, Google Scholar, and JSTOR specifically for articles on consanguinity in India. Articles on consanguinity types, prevalence, determinants, pregnancy, reproduction, medical disorders, congenital defects, and recent changes were researched with specific filters for our areas of interest. We meticulously filtered and searched all relevant publications from 2001 up to the 2024. A few older references were used because of their importance in relation to consanguinity. Majority of the publications were found in journals, online articles as well as in book chapters. Many of the studies were conducted on national-level data, and others were based on local community-level data. All the articles were checked carefully.

Each search engine had a different citation style prepared, such as APA, MLA, Chicago, Harvard, and Vancouver. The reference management software Mendeley was used for reference management in the text.

Prevalence of consanguineous marriage

Consanguineous marriage is practiced worldwide in varying degrees. Bittles & Black (2010) observed that the prevalence of consanguineous marriage is around 10%. Banerjee & Roy (2002) observed that one out of six marriages were consanguineous marriage in India. Using national level data (NFHS-4 Data), Sharma et al. (2020) found that consanguineous marriage was around 10.0%. Sharma et al. (2020) also observed regional variation in the prevalence of consanguineous marriage in different regions of India, such as in North (13.1%), Central (22.0%), Eastern (23.4%), North-east (3.1%), Western (14.8%), and South (23.6%). In multicultural habitat like India, consanguineous marriage varies depending on cultural practice and community level (Reddy et al. 2006; Kalam & Roy, 2014, 2016; Kalam & Ghosh, 2022). For example, Kalam (2021) found 34.0% marriage were consanguineous among the Darbhangia Khotta Muslim population of Malda district of West Bengal: around 11.0% of marriage among migrant Muslims of Mirzapur village in

Balasore district of Odisha. In South India, Kumaramanickavel et al. (2002) also found 28.0% of consanguineous marriage. Sahoo et al. (2022) found district wise variation in the prevalence of consanguineous marriage in South India.

Table 1: Prevalence of consanguineous marriage in India

Authors	Prevalence	Data
Kalam et al. (2024)	13.6%	Pan Indian
Sharma et al. (2020)	9.9%	Pan Indian
North India	13.1%	
Central India	22.0%	
East India	23.4%	
North-eastern India	3.1%	
West India	14.8%	
South India	23.6%	
Kalam (2021)	34.00%	Regional
Das (2003)	35.5%	Regional
Kumaramanickavel et al. (2002)	28.8%	Regional
Banerjee & Roy (2002)	16.6%	Pan Indian

Types of consanguineous marriage

Consanguineous marriage can be classified into first-cousin, second cousin, and uncle-niece marriage, etc. Most common type of consanguineous marriage is first cousin marriage. Sharma et al. (2020) found around 8.6% of marriages was first cousin marriage, followed by 0.7% second-cousin marriage and 0.6% of marriage was uncle-niece marriage. In local, regional level, Metgud et al. (2012) observed that around 52.0% of marriages were contracted marriage between first cousins among the rural women of Belgaum District of Karnataka. Kalam (2021) found around 92.0% of marriage among first cousins among Darbhangia Khotta Muslims of Malda district of West Bengal. Other rare types of consanguineous marriages were first-cousin once removed, double first-cousin, double second cousin (Figure 2a).

When studying anthropology, consanguinity types can take different forms, such as parallel and cross-cousin marriages. Parallel cousins are the children of siblings of the same sex, while cross-cousins are the children of siblings of the opposite sex. On the other hand, consanguineous marriage can be identified based on ego. In patriarchal Indian society male is the ego and consanguinity can be identified as MSD (Mother's Sister's Daughter), FBD (Father's Brother's Daughter), MBD (Mother's Brother's Daughter), FSD (Father's Sister's Daughter) (Figure 2b).

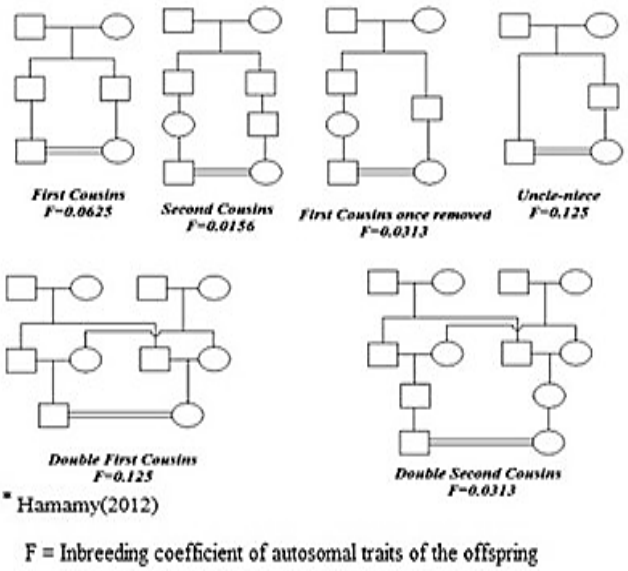

Figure 2a: Types of consanguineous (Hamamy 2012)

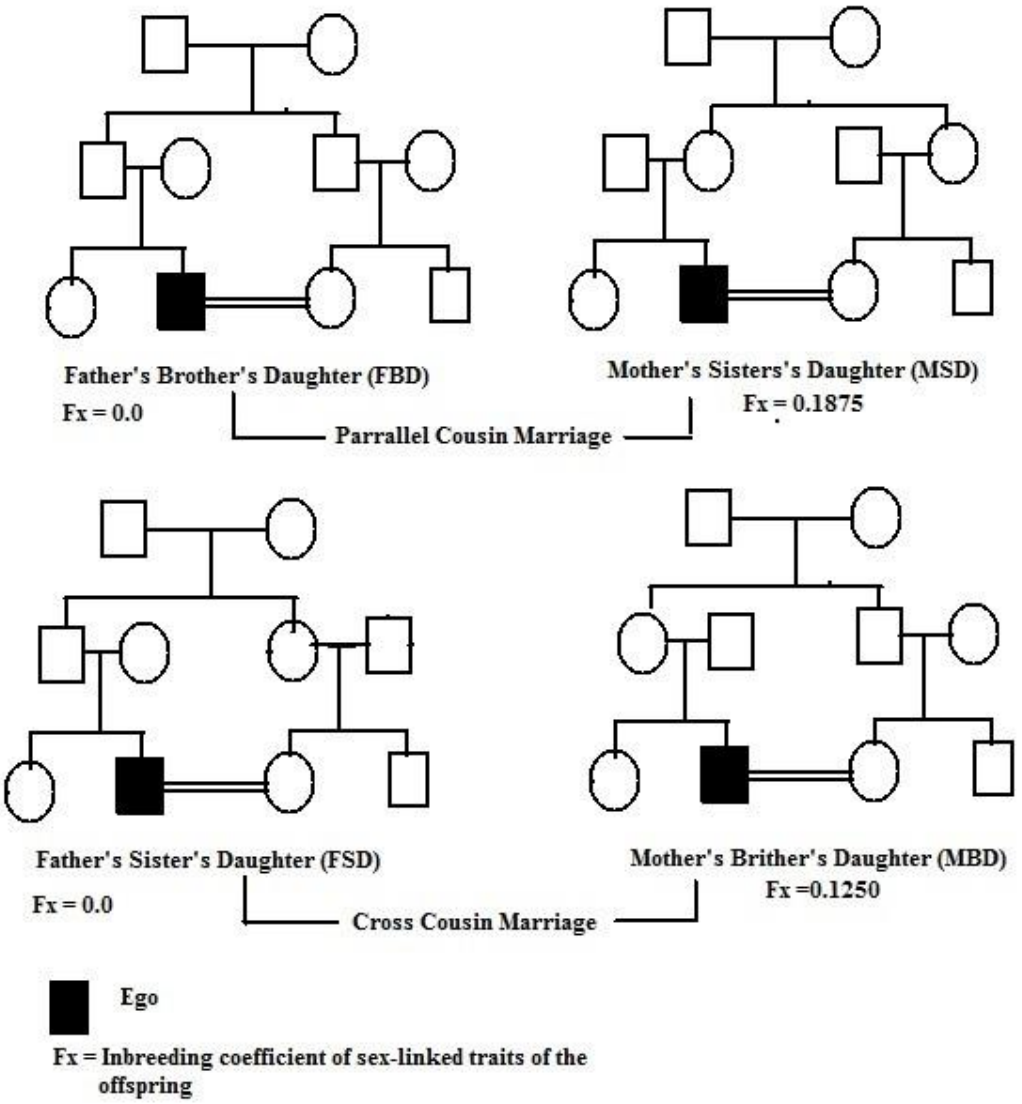

Figure 2b: Types of consanguineous marriage based on kinship relation (depending on *Ego*)

Factors contributing consanguineous marriage

a. Socio-demographic factors

Studies found several factors that contributed in the prevalence of consanguineous marriage in India (Banerjee & Roy, 2002, Sharma et al. 2020; Sahoo et al. 2022). Earlier studies found consanguineous marriage significantly higher among the respondents who were married earlier, having lower level of educational attainments, living in rural areas, and economically poorer condition of wealth status (Banerjee & Roy 2002; Sharma et al. 2020).

b. Religious factor

Studies found significant differences in the prevalence of consanguineous marriage among religious groups (Banerjee & Roy, 2002; Kuntla et al. 2013; Sharma et al. 2020; Kumari et al. 2020; Sahoo et al. 2022). In India, studies found that consanguineous marriage were two times higher among the Muslims compared to Hindus (Sharma et al. 2020; Kumari et al. 2021). It is a believed among Muslims; cousin marriage could possibly be described as an example provided by the sunnah (practical activity) of the Prophet (Bittles, 2012). It is believed that among six wives of the Prophet, two were biological relatives. He also married his daughter Fatima to his paternal first cousin Ali (Bittles, 2012). On the

other hand, among the Hindus of South India, the prevalence of consanguineous marriage was high (Hamamy et al. 2011; Sahoo et al. 2022). Kalam et al. (2020) found the prevalence of consanguineous marriage was around 3.0% among the other religious group i.e., combination of Christianity, Jainism and Buddhism.

c. Socio-cultural factors

Consanguinity also significantly influenced by the cultural practice of a community. Several local and community level studies observed that maintaining social cohesion, familial peace, better relationships with in-laws, and economic advantages relating to dowry, seem to be strong contributory factors in the preference for consanguineous unions (Srinivasan & Lee, 2004; Kalam & Roy, 2014; Hamamy et al. 2011). Srinivasan & Lee (2004) observed in Northern province of Indian state Bihar that families who are blood relatives are more likely to support consanguinity, because of the small amount of dowry, as the groom's parents refrain from making excessive demands due to close blood relation (Srinivasan & Lee, 2004). In such marriages, the bride's parents can have some say in how the dowry is used, benefiting the newly married couple, instead of only the groom's family (Srinivasan & Lee, 2004). Social security during old age is an important predictor of consanguineous marriage in India (Kalam, 2021). Consanguinity helps in the maintenance of regular communication between two families having common ancestors. Kalam (2021) found that consanguinity helps in maintenance of familial as well social solidarity among the migrant Darbhangia Khotta Mulims of Malda district of West Bengal. It has also observed that population in community level marry their cousins due to unavailability of same cultural group in migrated place, to maintain cultural identity (Kalam et al. 2020). However, recent study from pan India data argued that consanguineous marriage significantly positively related to the spousal violence in Indian continent (Rahaman et al. 2020), but the scenario might be different in small scale community level studies (Kalam, 2021).

Reproductive consequences of consanguineous marriage

Consanguineous marriage is an important subject matter among the scientist due to its reproductive consequences (Hussain et al. 2001; Banerjee & Roy, 2002; Saggar et al. 2008; Mumtaz et al.2010; Bellad et al. 2011; Kuntla et al. 2013; Fareed et al. 2017).Studies found that there is higher likelihood of pregnancy loss and health defects among the child of consanguineous couples (Banerjee & Roy 2002; Kuntla et al. 2013; Fareed et al. 2017; Islam, 2013; Teeuw et al. 2014; Oniya et al. 2019; Anwar et al. 2020).

a. Pregnancy loss or wastage

Using pan Indian data, Banerjee & Roy (2002) explores that consanguinity significantly negatively affects child survivality. Banerjee & Roy (2002) found that stillbirth, neonatal mortality and post neonatal mortality was significantly higher among the close biological relatives. However, there are several exogenous (i.e., socioeconomic, environmental, availability and utilization of health care services) and endogenous (i.e., inbreeding, birth injury, etc) factors that affects mortality (Stockwell et al. 1987; Kalam et al. 2024). Controlling exogenous factors, studies found consanguinity negatively affects child survivals in India (Kuntla et al. 2013; Fareed et al. 2017). Kalam et al. (2024) observed that consanguineous marriage significantly negatively affects stillbirth/spontaneous abortion, neonatal mortality as well as post-neonatal mortality, and distant consanguinity affects more compared to close consanguinity. Das (2006) found that spontaneous abortion, stillbirth, infant mortality was significantly higher among consanguineous couples, whereas the effect was not significant among child and juveniles. In South India, Bellad et al. (2011) found that non-consanguineous marriages had fewer stillbirth and lower rates of miscarriages. Fareed et al. (2017) also found higher mortality rates among the consanguine families than non-consanguine families.

b. Fertility

Consanguinity significantly affects the fertility behaviour among the couples. Earlier studies show fertility was significantly higher among consanguineous

marriages than non-consanguineous marriage (Hussain & Bittles, 2004; Bharathi, 2014; Jaber & Halpern, 2014). Bharathi (2014) found that fertility was higher among consanguineous couples that non-consanguineous couples among the Khond population of Andhra Pradesh. Kalam (2021) also found higher fertility rate among consanguineous couples those non-consanguineous couples among the Darbhangia Khotta Muslim population of West Bengal. Bittles et al. (2002) significantly concluded from study on thirty population that fertility was higher among consanguineous couples that non-consanguineous couples.

c. Medical disorders

Consanguinity if found to be associated with several medical disorder (Kumaramanickavel et al. 2002; Nirmalan et al. 2006; Mamidala et al. 2014; Lakhan et al. 2017). Mamidala et al. (2014) found that consanguinity increases the risk for autism spectrum disorder (ASD) with an odds ratio of 3.22. Kumaramanickavel et al. (2002) found that consanguinity increases the risk of ophthalmic genetic disorders. Lakhan et al. (2017) explored that intellectual disability was significantly higher among the couples married within biological relation. Bellad et al. (2011) also observed that non-consanguineous marriages show lower incidences of low birth weight among children. It was observed that in consanguineous marriages, there was 0.85%, 0.84%, 1.57% 0.43%, 0.34%, and 0.14% chances of their children and grandchildren developing psychotic disorders, heart disease, hypertension stroke, cancer, and diabetes, respectively (Kundu & Jana 2024). Rauniyar & Das (2022) found that the most common ocular disorders associated with a high proportion of consanguinity were congenital hereditary endothelial dystrophy (CHED) (100%), corneal macular dystrophy (83.78%), xeroderma pigmentosum (80.95%), and ocular albinism (73.59%).

d. Congenital malformations

Consanguinity is found to have significantly associated with congenital abnormalities (Amudha et al. 2005; McGregor et al. 2010; Ashraf et al. 2010; Sinha & Singh, 2013). Amudha et al. (2005) found that congenital abnormality is significantly influenced by consanguinity. Sinha & Singh (2013) also found significant association between congenital malformation and consanguineous marriages. Findings from South India reveal that first-cousin marriages and uncle–niece marriages are equally significant in increasing congenital heart diseases (Ramegowda & Ramachandra, 2006). Shamnas et al. (2013) observed that congenital defect often occurs because of consanguinity in Indian population. It was observed that congenital permanent hearing impairment was three times higher in first degree, second degree and two times higher in third degree consanguinity (Selvarajan et al. 2013). Recent study shows around 4.55% of the individuals have a history of birth defects or congenital disorders having history of consanguinity (Kundu & Jana, 2024).

Recent trends in consanguinity

It was observed around the world that consanguineous marriage is declining over the years (Bittles & Black 2012). The practice of consanguineous marriage has decreased over the years (Kalam et al. 2020; Kumari et al. 2020). According to Kalam et al. (2020), using pan-Indian data, consanguineous marriage declined by about sixteen percent in nearly two and a half decades. Improvement in educational opportunities significantly effects in the decline of consanguinity in India (Kumari et al. 2020). Additionally, local community level study shows a generational decline from 33.3% to 12.5% in consanguineous marriage among the Darbhangia Khotta Muslim population of West Bengal (Kalam et al. 2017). Among the Sunni Muslims of West Bengal, an overall declining trend in consanguinity has been observed. There are several reasons cited for the declining prevalence of consanguineous marriage, such as modernization (Goode, 1963), low compatibility among couples (Kalam & Roy, 2014), increased depression among couples (Rao et al. 2009) and exposure of the young generation to the outer world (Kalam, 2021). Consanguineous marriages often lead to family conflicts and social stigma, resulting in the fear of such unions (Kalam, 2021).

Consanguinity and Index of opportunity for selection

Consanguinity is often decreasing the vigour or effectiveness of a population (Wright, 1922). The effectiveness of natural selection in a population can be

measured using estimates of differential fertility and differential child mortality which is known as the index of opportunity for selection (Crow, 1958). Lower value of index of total selection intensity shows fewer changes in the genetic makeup of a population (Faredd et al. 2017). Study from Uttar Pradesh, North India shows lower selection intensities among populations of consanguineous groups in comparison with the non-consanguineous ones (Arzoo & Afzal 2006). Among a fishing community of Vigianagram district of Andhra Pradesh, Nahari and Aprna (2005) found higher value of index of opportunity for selection in consanguineous groups that non-consanguineous groups. Rajeswari et al. (2015) found variation in the total selection intensity among two population of Andhra Pradesh. Among the Yadava's the value of selection intensity was higher in consanguineous couples that non-consanguineous where among the Vadabalija's, the value of selection intensity was nearly triple in consanguineous couples than non-consanguineous couples (Rajeswari et al. 2015).

Legal regulation in consanguineous marriage

Legislation enacted at the national level often faces challenges in implementation, as demonstrated by the Hindu Marriage Act of 1955, which prohibits uncle-niece marriages (Kapadia 1958). Despite this, studies conducted from the 1980s onward in Bangalore and Mysore, the two major cities of Karnataka in southern India, revealed that 21.3% of Hindu marriages involved uncle-niece unions (Bittles et al. 1992). Consanguineous marriages are deeply rooted in the customs of southern India, particularly among communities south of the Narmada River. While the Hindu Marriage Act of 1955 recognized cross-cousin marriages, the legality of uncle-niece unions was later affirmed by the Hindu Code Bill of 1984 (Rao et al. 2002). For Muslims, cousin marriages are permissible under Sharia law. However, a Muslim man is prohibited from marrying specific blood relatives, including his mother, grandmother, daughter, granddaughter, sister, niece, great-niece, aunts, or great-aunts. Marriages are also prohibited with relatives through marriage, such as his wife's mother or grandmother, wife's daughter or granddaughter, and his son's wife, particularly in cases of subsequent marriages. Additionally, foster relationships follow similar restrictions to those applied to blood and marital relations, including foster sisters or daughters of a foster mother.

Concluding remarks

Consanguineous marriage i.e., marriage between close blood relatives, is still practised in many societies, despite its numerous detrimental effects on pregnancy and congenital disorders. Consanguineous marriage has many positive socio-cultural outcomes. It can help maintain solidarity within the community, often promoting peace in the family, reducing the burden of dowry in patriarchal societies, and providing old-age security for in-laws. However, in low-income countries like India, the low literacy rate among rural people leaves them unaware of the negative effects of consanguinity, leading to a preference for consanguineous marriages. Due to their limited understanding, consanguineous couples often attribute pregnancy issues to a higher power, i.e., God, rather than recognizing the negative impact of consanguinity.

The practice of consanguineous marriage has decreased over the years, particularly among the younger generation, reflecting a positive trend towards more diverse and varied relationships. The younger people often migrate to urban areas for higher education or better job opportunities, which might negatively affect the acceptance of cousin marriages. Increasing women's decision-making power in the twenty-first century may also result in a decrease in consanguineous marriages. However, further research at the community level is crucial to uncovering the socio-cultural impacts of consanguineous marriage and understanding how consanguinity affects family relations.

This review paper explores and assesses the comprehensive knowledge of consanguinity in the twenty-first century. After learning about the harmful effects of close relatives marrying, concerned couples and family members were motivated to seek genetic counselling for a better future, while also involving policy makers.

Acknowledgments

The authors acknowledge the anonymous referees for providing insightful comments in the earlier draft of the paper

Financial disclosure and conflict of interest

This research did not receive any specific grant from any funding agency, commercial entity or nor-for-profit organization.

The authors of this paper do not have any conflicts of interest.

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