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**COGNITIVE AND BEHAVIORAL CHANGES IN
AGING: EMOTIONAL PROCESSING, TIME
PERCEPTION, AND DECISION-MAKING**

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ABSTRACT

Aging is a complex and multifaceted process that influences various aspects of cognition and behavior. The present doctoral thesis aims to explore the cognitive and behavioral changes associated with aging, focusing on the impact of aging on emotional processing, face recognition, time perception, and decision-making. The research highlights how older adults differ from younger individuals in the recognition and interpretation of emotional stimuli, showing a bias toward positive emotional content—commonly referred to as the “positivity effect”—as predicted by Socioemotional Selectivity Theory.

The findings also reveal age-related shifts in temporal cognition, with older adults demonstrating a tendency to prioritize emotionally meaningful experiences while de-emphasizing or delaying negative ones. These changes in time perception are reflected in decision-making strategies, which tend to favor personal relevance and emotional well-being, sometimes at the cost of exhaustive analysis or consideration of all available information.

Additionally, the thesis examines potential avenues for mitigating cognitive decline through non-invasive brain stimulation techniques, such as transcranial alternating current stimulation (tACS), gamma sensory stimulation (GSS), and transcranial magnetic stimulation (TMS). These interventions show promise in enhancing specific cognitive functions, particularly episodic memory, in individuals with age-related neurodegenerative conditions such as Alzheimer’s Disease and Mild Cognitive Impairment.

Overall, the present work adopts an integrated, multidisciplinary approach to studying the cognitive and emotional impacts of aging. From a clinical perspective, the thesis contributes to understanding how aging affects cognition and behavior, providing insight into how cognitive decline can be mitigated through emotional regulation strategies. From a cognitive perspective, the thesis adds to the understanding of how emotional processing, face recognition, and time

perception change with age. Finally, from a behavioral perspective, the research investigates the implications of these cognitive changes for decision-making, emphasizing the role of emotional regulation in older adults' choices. The findings presented in this thesis have implications for designing interventions that support older adults in navigating the cognitive and behavioral challenges of aging, enhancing both their cognitive performance and emotional well-being.

INTRODUCTION

Human cognition and behavior are shaped by a wide range of factors, reflecting the incredible complexity and adaptability of the human brain (Shettleworth, 2009). As an extremely plastic organ, the brain can respond to environmental changes, adapt to new experiences, and dynamically reorganize itself based on lived events and external stimuli, in a process known as neuroplasticity (Mateos-Aparicio & Rodríguez-Moreno, 2019; Nava & Röder, 2011). This ability ensures that the brain remains responsive throughout life, enabling individuals to learn, grow, and adapt to challenges (Puderbaugh & Emmady, 2024). In addition to neuroplasticity, changes at the genetic and epigenetic levels also play a critical role in shaping cognitive and emotional traits (Baye et al., 2011; Orgogozo et al., 2015). Research in these fields has shown that gene expression and molecular mechanisms can be modulated by environmental factors, such as stress, nutrition, and social interactions, which in turn influence brain structure and function over time (Hoeijmakers et al., 2015; Yam et al., 2015). Cognitive processes are also deeply interconnected with human behavior, as individuals make decisions, regulate emotions, and interact with others in ways that reflect both internal mental states (e.g. thoughts, emotions, beliefs, and motivation) and environmental influences (Forgas, 2002; Osman, 2010; Reis et al., 2000). Behavior, however, is not only a stimulus-response process; it evolves over time through learned patterns, habits, and coping mechanisms shaped by long-term experiences and social contexts (Toates, 1997). These variables—including genetic, epigenetic, and environmental factors—continuously influence and modify cognitive processes, highlighting the dynamic interplay between internal and external factors shaping the human brain.

Among these influences, one of the most significant variables influencing brain processes and cognitive functions is aging (Craik & Bialystok, 2006), which leads to both structural and functional changes. Structurally, a progressive reduction in gray and white matter volume is observed (Salat et al., 2009), along with a decrease in synaptic density and neuronal connections

(Masliah et al., 2006), which can affect various cognitive functions, including memory, processing speed, and executive functions (Murman, 2015). Functionally, aging is accompanied by greater recruitment of frontal brain regions during complex cognitive tasks and reduced lateralization in anterior brain regions (Cabeza, 2002; Grady et al., 1994), indicating that older adults compensate for declines in other regions by utilizing additional neural resources (Spreng & Turner, 2019; Zarahn et al., 2007). This compensatory recruitment is a form of functional adaptation, where older adults engage more neural circuits to perform tasks that younger individuals can complete with fewer resources (Li et al., 2001).

Structural and functional changes can lead to a modulation in cognitive performance, such as difficulties in memory consolidation and retrieval or impairment in decision-making (Balota et al., 2000; Denburg et al., 2005). In this context, emotion regulation plays a pivotal role in mitigating the impact of these changes, acting as a buffer that supports cognitive and behavioral adaptability (Lantrip & Huang, 2017; Peters et al., 2007). At a cognitive level, emotionally salient events are processed and stored more effectively than neutral ones (Di Domenico et al., 2015; Mammarella et al., 2016, 2017; Reed & Carstensen, 2012). Healthy older adults, in fact, exhibit a phenomenon known as the '*positivity effect*', which refers to their tendency to focus on and remember positive information more than negative or neutral stimuli (Carstensen & Turk-Charles, 1994). This effect is framed in the literature within the Socioemotional Selectivity Theory (SST), which posits that as perceived time grows shorter with age, individuals prioritize present-oriented goals related to emotional satisfaction and meaning over future-oriented goals, leading to a greater focus on and memory for positive information (Carstensen, 1993; Reed & Carstensen, 2012). Older adults demonstrate enhanced cognitive performance when processing emotionally charged stimuli compared to neutral ones, as emotionally salient content strengthens encoding and recall processes, even in the presence of age-related decline. Notably, their performance in processing emotionally salient stimuli is comparable to that of younger individuals. (Carstensen & Turk-Charles, 1994; D'Argembeau &

Van Der Linden, 2004; Kensinger et al., 2002). Similarly, in tasks involving the recognition of emotional faces, older adults often perform better when recognizing positive expressions like happiness, as opposed to neutral or negative ones (Di Domenico et al., 2015; Mather & Carstensen, 2003). In decision-making tasks framed with emotional implications—such as evaluating options with positive outcomes— older adults often elicit quicker and more accurate cognitive evaluations compared to neutral contexts (Mikels et al., 2015). In fact, when making decisions, older adults tend to approach the process differently from younger individuals. They are less exhaustive in their search for information, often opting to consider fewer options (Reed et al., 2013) and reviewing less data overall before deciding more quickly (Mata et al., 2012). Their choices are often influenced by a preference for personally relevant information (Hess et al., 2013), although they are less aware of the sources of that information (Cansino et al., 2013). Interestingly, after a decision is made, older adults report greater satisfaction with their choices and experience less regret compared to younger individuals (Brassen et al., 2012; Löckenhoff & Rutt, 2015). Thus, the age-related '*positivity effect*' benefits choice satisfaction. However, this heightened satisfaction can sometimes limit their ability to learn from poor outcomes, particularly when those outcomes are ambiguous (Delpero et al., 2015).

Cognitive changes also extend to behavioral patterns, particularly in the domain of social interactions, where older adults exhibit distinct tendencies. Older adults generally report higher satisfaction with their social connections, experiencing fewer negative interactions and recalling more positive emotions with close partners compared to younger adults (Birditt et al., 2005). They perceive greater support from their close relationships as they age, finding deeper fulfillment in relationship (Field & Minkler, 1988; Schnittker, 2007). These shifts reflect a prioritization of emotionally rewarding experiences over less meaningful interactions, aligning with the natural tendency in older adulthood to focus on emotional well-being and stability (Baltes & Baltes, 1990; Carstensen et al., 1999). Emotions also significantly influence older adults' decreasing drive to seek out novelty. The elderly show less openness to new experiences

(Costa et al., 2000; Donnellan & Lucas, 2008), reduced curiosity (Camp et al., 1984), and diminished enthusiasm for thrill-seeking or variety-seeking behaviors (Novak & Mather, 2007; Giambra et al., 1992), which can be understood as a strategy to maintain emotional equilibrium. Avoiding uncertainty or high-stakes novelty may reflect a preference for environments and activities that reinforce positive emotional states and minimize stress.

In light of the complex and multifaceted effects of aging on cognition and behavior, the present doctoral thesis aims to explore how age-related changes influence emotional processing, facial recognition, time perception, and decision-making. These processes are integral to our understanding of how older adults respond to environmental stimuli and make cognitive and behavioral judgments across various contexts.

In Chapter 1, I will explore how aging affects the categorization of emotions in dynamic facial expressions and identity recognition under conditions of facial occlusion. By investigating these differences across younger and older adults, this chapter highlights the challenges posed by facial occlusion in both emotion categorization and face recognition, providing insight into the differential neural processing of these tasks in aging.

In Chapter 2, I will examine the processes involved in emotional recognition, specifically focusing on the cortical and subcortical routes for processing facial emotions and the effects of aging on these pathways. This chapter will present a contribution of how age-related changes in facial emotion recognition, and the use of High and Low Spatial Frequencies (HSF and LSF) will allow for a deeper understanding of the perceptual differences between younger and older adults.

Chapter 3 will investigate how aging influences the scheduling of emotionally valenced activities, including how older adults differ from younger adults in terms of planning positive and negative events. This chapter will also examine the impact of cognitive changes, such as the positivity effect, on individuals' preferences for temporal scheduling, contributing to the growing understanding of how older adults prioritize emotional events.

In Chapter 4, the focus shifts to how aging impacts temporal perception, particularly in the estimation and manipulation of time intervals. Using a set of temporal judgment tasks (e.g., time reproduction, bisection, and doubling), this chapter will explore how older adults perform relative to younger adults and the cognitive mechanisms, such as working memory and attentional control, that may explain age-related differences in time processing.

Chapter 5 will explore the cognitive and neural aspects of interventions targeting cognitive impairment, particularly in Alzheimer's Disease and Mild Cognitive Impairment. This chapter will present a systematic review of gamma oscillation modulation techniques, such as transcranial alternating current stimulation (tACS), gamma sensory stimulation (GSS), and transcranial magnetic stimulation (TMS), to explore their potential in enhancing cognitive functions, particularly episodic memory, in older adults with neurodegenerative conditions.

To summarize, this doctoral thesis takes an integrated and multidisciplinary approach to understanding age-related cognitive and emotional changes. Understanding the effects of aging on cognition and behavior requires a framework that accounts for the interrelated nature of emotional, perceptual, and decisional processes. Rather than examining isolated cognitive functions, this thesis embraces a holistic perspective that views aging as a dynamic interaction between neural adaptation, emotional regulation, and behavioral strategies. It explores this compensatory-emotional dynamic across four interrelated cognitive domains: emotional processing, face recognition, time perception, and decision-making. These domains represent key touchpoints in the daily cognitive experiences of older adults. Emotional processing and face recognition are central to social interaction and empathy; time perception influences planning, goal setting, and subjective well-being; and decision-making reflects the culmination of perceptual, emotional, and executive processes. Collectively, they allow for a comprehensive investigation of how aging shapes the interpretation of the present, the recollection of the past, and the anticipation of the future. By examining these areas through both behavioral and

neurocognitive perspectives, this thesis aims to generate a unified understanding of aging not as a linear decline, but as a complex adaptation characterized by selective optimization of cognitive resources.

From a clinical point of view, this work aims to identify areas where cognitive decline is most pronounced and provide insights into potential interventions. From a behavioral perspective, it will offer valuable information on how older adults make decisions and allocate their time and emotional resources. Ultimately, this research seeks to advance our scientific knowledge of cognitive aging and inform practical interventions that can support older adults in managing these changes.

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CHAPTER 1: From Emotional Detection of Dynamic Stimuli to Facial Identity Recognition: Age Difference in the Processing of Partially Occluded Faces

As described in the Introduction, aging is associated with significant cognitive and behavioral changes, particularly in the domains of emotion processing. Although numerous studies have been conducted, gaps remain in understanding how these age-related changes influence complex tasks like emotion recognition and identity processing, especially under challenging conditions such as facial occlusion. The ability to interpret dynamic emotional cues and recognize familiar faces is critical for effective social interaction, yet these processes may be differentially affected by aging.

Chapter 1 seeks to address these gaps by investigating age-related differences in emotion categorization and facial identity recognition, under the condition of facial occlusion. By using dynamic and static facial stimuli with varying levels of coverage, this study aims to explore how occlusion impacts the ability of younger and older adults to process emotional expressions and recognize previously encountered faces. The findings will elucidate the distinct cognitive mechanisms underlying these tasks and offer new insights into the strategies employed by older adults to compensate for age-related declines in facial processing.

1. Introduction

Faces provide an amount of information that facilitates social communication, and the ability to process such information may represent one of the most highly developed visual skills

in humans (Haxby et al., 2000). A fundamental information conveyed by faces is the type of emotion they are expressing (Prete & Tommasi, 2018), together with other information such as age, gender, ethnicity, and so on (Prete, 2017; Prete et al., 2016; Prete & Tommasi, 2019). This information is crucial for memorizing and recognizing individuals in subsequent interactions, enabling people to build and maintain social relationships. Recognizing who a person is and understanding their emotional state depend on the visual processing of facial cues (Abudarham & Yovel, 2019; Wegrzyn et al., 2017). Therefore, factors that affect the perception of facial identity, such as visual occlusion, modulate both emotion categorization and face recognition performances (Carbon, 2020; Di Crosta et al., 2023; Ventura et al., 2023). Previous studies have also identified age-related differences in facial emotion detection and face recognition, with older adults generally exhibiting lower accuracy in both abilities (Grainger et al., 2017; Lin et al., 2020).

The present study aims to build on previous research by (i) enhancing ecological validity through the use of dynamic facial stimuli and (ii) examining how different types of visual occlusion affect emotion recognition accuracy and subsequent face memory. First, we examined how younger and older adults categorize emotions displayed in short videos of developing facial expressions, presented either as whole faces or with partial occlusions. Specifically, we explored the differential impact of a surgical mask and a blank cover on the lower face on emotion recognition across age groups. Subsequently, through a discrimination task, we evaluated the extent to which younger and older adults recognize previously viewed faces, comparing stimuli originally presented as either whole or occluded, as well as comparing different emotions

2. Literature Review

Accuracy in identifying emotions plays a crucial role in regulating social interactions and significantly influences individual's behaviors during social interactions (Marzoli et al., 2022;

Van Kleef, 2009). Facial cues, including the subtle movements of specific muscles in the eye, nose, and mouth, convey distinct emotional information (Ekman & Oster, 1979). However, research has demonstrated that, while faces are rich in emotional cues, our ability to accurately assess the emotional state based solely on facial information is far from perfect (Derntl et al., 2009). Context, for instance, significantly influences our capacity for expression analysis (Aviezer et al., 2008). Additionally, it has been shown that static views of faces, without information regarding the dynamic progression of expressions, impair our accuracy in reading emotions (Blais et al., 2017). Partial occlusions of the face, such as sunglasses (Noyes et al., 2021) or scarves (Kret & De Gelder, 2012), further present obstacles in the correct interpretation of facial expressions. In recent years, due to COVID-19 pandemic, the use of surgical masks, covering approximately 60-70% of the face (Prete et al., 2020), posed a significant challenge to emotion recognition in everyday life (Grahlow et al., 2022; Henke et al., 2022; Marini et al., 2021; Prete et al., 2022; Ventura et al., 2023). Additionally, masks may be perceived as a threatening stimulus (Cannito et al., 2020), potentially having a distinct impact on emotion recognition (Grahlow et al., 2022). Beyond emotional interpretation, researchers have investigated whether masks affect facial identity processing: the findings in this regard have been mixed, with some studies indicating a significant reduction in memory for faces seen partially covered (Marini et al., 2021), while others do not observe any significant differences (Noyes et al., 2021; Ventura et al., 2023). The variability in results points to the possibility that emotion categorization and facial identity recognition rely on distinct cognitive processes, a possibility aligns with the widely accepted functional model of face recognition proposed by Bruce and Young (1986). This model suggests that the recognition of emotional expressions and facial identity constitutes distinct perceptual processes encoded by separate psychological and neural mechanisms. Emotion recognition heavily relies on highly mobile facial regions, such as the eyes and mouth, which are processed by the superior temporal sulcus. In contrast, facial identity recognition primarily depends on invariant, static facial traits, such as the distance between the

eyes or the shape of the jawline, which are processed by the fusiform gyrus (Bruce & Young, 2012; Haxby et al., 2000).

Empirical evidence demonstrates that older adults encounter greater challenges in both recognizing emotional expressions and accurately identifying faces (Grainger et al., 2017; Lin et al., 2020). Indeed, older adults show increased difficulties in recognizing basic emotions (Ruffman et al., 2008) and neuropsychological findings suggest that these challenges may be linked to volume reductions in temporal areas, including the amygdala and fusiform gyrus (Li et al., 2016; Liu et al., 2018; Petrovic et al., 2008; Ruffman et al., 2008), which could potentially reduce activation during emotion matching tasks. These regions are crucial for emotion-matching tasks: the amygdala is involved in the detection and processing of emotional expressions, while the fusiform gyrus is responsible for facial identity and emotional expression recognition (Ruffman et al., 2008). Volume reductions in these areas may lead to diminished activation, impairing the ability to process emotional faces and subsequently affecting emotion recognition in older adults.

Recent research has highlighted that age-related differences in emotion categorization persist even when dynamic facial cues are presented, underscoring the robustness of these effects across more ecological conditions. Studies using dynamic stimuli have shown that older adults tend to exhibit reduced accuracy, especially for negative emotions, suggesting that more ecological information does not necessarily compensate for age-related perceptual declines (Grainger et al., 2017; Richoz et al., 2018). However, when older adults are presented with pairs of face photographs, they tend to exhibit an attentional bias towards happy expressions rather than the negative ones, a phenomenon that has been labeled ‘positivity effect’ (Mather & Carstensen, 2003). It has been argued that this effect might serve as an adaptive strategy aimed at preserving emotion regulation and minimizing social conflict (Carstensen et al., 2006). Moreover, when faces are partially covered, older adults tend to perform worse than younger

adults in recognizing emotions that rely on information from the lower part of the face (e.g., sadness and disgust) (Faustmann et al., 2022; Henke et al., 2022; Slessor et al., 2022). This suggests that older individuals utilize information from the mouth region differently compared to younger adults.

Regarding face memory recognition, there are conflicting findings concerning differences between younger and older individuals: older individuals often exhibit reductions in recognition memory for unfamiliar faces (Grady et al., 2002; Lamont et al., 2005). However, it is worth noting that the typical age-related decline in episodic memory is, at least partially, influenced by the nature of the stimuli employed. On the one hand, positive stimuli, including faces with positive expressions, tend to be better remembered by older adults (Denkinger & Kinn, 2018; Di Domenico et al., 2015; Durbin et al., 2020; Ebner & Johnson, 2009; Mannion et al., 2023); on the other hand, some studies have reported no differences between age groups, suggesting that salient information, such as emotional salience, plays an important role on memory recognition (Carstensen & Turk-Charles, 1994; D'Argembeau & Van Der Linden, 2004; Denkinger & Kinn, 2018; Hargis & Castel, 2017).

The present study aims to explore age-related differences in facial emotion detection (Phase 1) and in the identification of previously viewed faces (Phase 2). Specifically, in Phase 1, we investigated age differences in categorizing emotions expressed in dynamic stimuli presented as whole faces and as occluded faces. The use of dynamic facial stimuli, as opposed to static faces employed in most of the referenced studies, reflects an effort towards a greater ecological validity, particularly given the influence of task design on observed age-related effects. The meta-analytic review by Hayes et al. (2020) demonstrates that tasks involving dynamic stimuli, longer exposure, or emotion matching tend to reduce the magnitude of age differences. Additionally, we explored whether different occlusion types have different effects on emotion recognition across ages, comparing the presence of a blank cover in the lower part of the face

(half faces) with the presence of a salient stimulus as a surgical mask (masked faces). This comparison was designed to isolate the effect of simply hiding the mouth area, without introducing the potential social or emotional connotation linked to masks (Cannito et al., 2020). In Phase 2, the goal was to explore age-related differences in recognizing static facial stimuli, encountered as dynamic in Phase 1, using a discrimination task. We hypothesized a higher overall accuracy in younger compared to older participants both in the perceptual processing of dynamic stimuli (phase 1) and in the recognition of static faces (phase 2), but we also expected a positivity bias in aging, characterized by greater sensitivity in discriminating previously encountered happy faces compared to other emotions, mainly for whole (compared to occluded) stimuli. This hypothesis is based on evidence suggesting that older adults rely more on information from the mouth region, which is critical for recognizing happiness, yet tend to perform worse when this region is obscured (Faustmann et al., 2022; Henke et al., 2022; Slessor et al., 2022).

To sum up, the present study offers a novel contribution by employing dynamic facial stimuli displaying emotional expressions, both with and without partial occlusions, to directly compare performance in young and older adults. This approach enables the examination of how partial occlusion influences emotion recognition and facial identity memory across the adult lifespan. By integrating two domains, emotion categorization and face recognition, within an ecologically valid context that reflects real-world challenges (e.g., widespread mask-wearing during the COVID-19 pandemic), this research addresses a gap in the literature. Moreover, it sheds light on whether these two cognitive processes operate independently or interactively, and how such interactions may be modulated by age-related perceptual and cognitive changes.

3. Materials and Methods

3.1 Participants

Prior to collecting data, we conducted an a priori power analysis using GPower 3.1.9.4 (Faul et al., 2007) to determine the minimum sample size required. The power analysis specifications were as follows: $f = 0.15$, power = 80%, $\alpha = .05$, and correlation among repeated measures = 0.5. The power analysis revealed that 68 participants would be needed.

The study was carried out by 61 Younger Adults (YA; 54 females, 18-35 years old) and 50 Older Adults (OA; 32 females, over 65-82 years old). We recruited a larger sample than initially required to account for potential exclusions due to performance, technical issues, or unmet inclusion criteria. Due to an inadequate response pattern, the sample size was reduced to 60 YA ($M = 24.77$, $SD = 4.56$) and 49 OA ($M = 73.88$, $SD = 7.34$).

Participants were recruited through word-to-mouth and online advertisements on social media, providing written informed consent. Exclusion criteria were a history of neurological and/or psychiatric disorders, drug or alcohol abuse, taking medications that could affect cognitive functions. The study collected socio-demographic information such as age, gender, and education level (measured using a 5-point scale ranging from elementary school to postgraduate degree). Older adults were included only with a score 18 or above at the Montreal Cognitive Assessment (MoCA) (Nasreddine et al., 2005). Participants completed questionnaires assessing their levels of positive and negative affect (PANAS) (Watson et al., 1988), depression (BDI-II) (Beck et al., 1996), and fear and concerning beliefs relating to the COVID-19 pandemic (Fear of COVID-19 questionnaire) (Di Crosta et al., 2020). For more information about the sample characteristics and scores see Table 1.

	Younger Adults (YA) <i>M (SD)</i> <i>N = 61 (54 females)</i>	Older Adults (OA) <i>M (SD)</i> <i>N = 50 (32 females)</i>	Statistics
Age	24.74 (4.53)	73.96 (7.29)	-
Education	4.87 (0.34)	2.87 (1.13)	$t_{(111)} = 13.24, p < .001$
MoCA	-	22.67 (4.93)	-
PANAS +	30.87 (7.01)	29.57 (8.38)	$t_{(111)} = .88, p = .378$

PANAS -	34.69 (7.29)	38.57 (8.95)	$t_{(111)} = -2.51, p = .014$
BDI-II	11.54 (7.53)	12.61 (11.85)	$t_{(111)} = -.58, p = .566$
Fear of COVID-19	44.97 (14.09)	43.49 (23.54)	$t_{(111)} = .41, p = .684$

Table 1. Sample Characteristics of the Study. Note. *M*=mean, *SD*=standard deviation. Statistics are separated for younger adults (YA) and older adults (OA).

3.2 Stimuli

The original faces were extracted from the FACES database (Ebner et al., 2010): photographs of faces with neutral, happy, angry, fearful, sad, and disgusted expressions were selected, for a final set of 80 stimuli. Half stimuli were female faces and half were male faces, and for each gender half were young and half were middle-age faces. From this set of stimuli, 40 displayed neutral expression and were presented as static images, the other 40 stimuli were morphed using Morpheus Photo Animation Suite (v3.17) and videos were created, in which starting from a neutral facial expression, a specific emotion was shown. We chose to create dynamic stimuli because, unlike available databases, this software allowed us to mark facial landmarks to perfectly align them, and to choose the duration of the video. Each video begins with a neutral expression and arrive to express 100% of the target emotion within 4000 ms: in 1000 ms, 25% of the final expression was expressed (see Figure 1). Half of the videos (N=20) was then manipulated to obtain Partial Stimuli: faces were covered by a surgical mask ('Mask' version) and by a white rectangular shape leaving visible only the upper portion of the stimulus ('Half' version; Figure 1). As a result, we obtained 20 Whole Stimuli (No-Mask), and 20 Partial Stimuli presented either as Mask or Half faces.

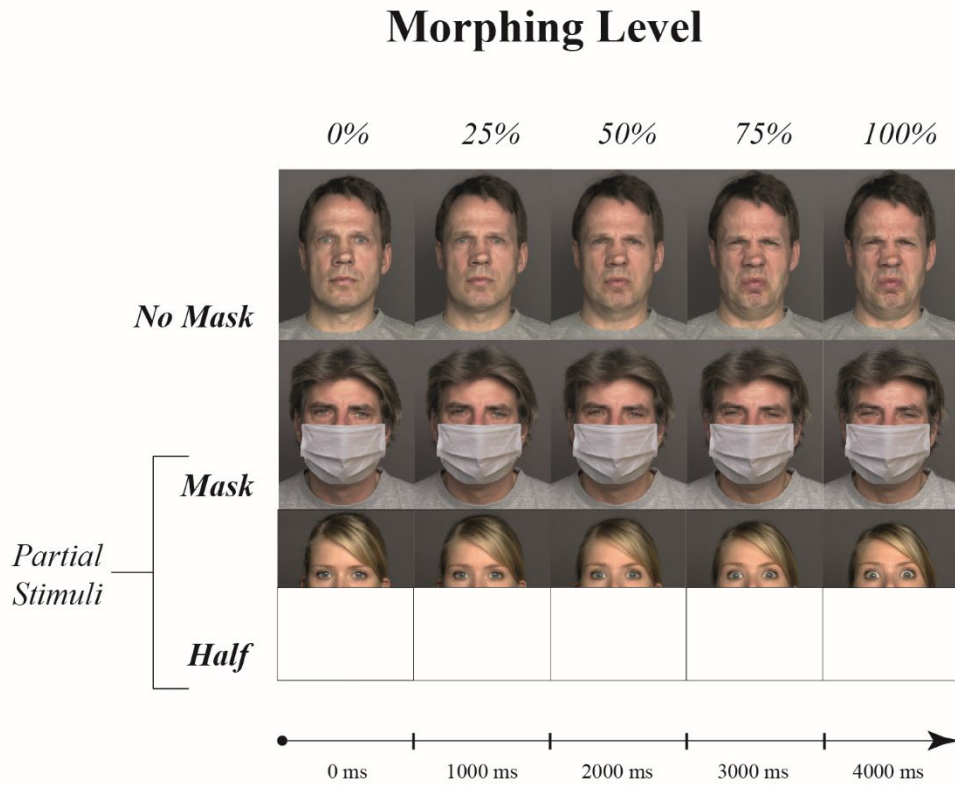


Figure 1. Example of dynamic stimuli (each second represents 25% of expressed emotion). First row: example of a Whole Stimulus (No-Mask); second row: example of a stimulus in which the surgical mask was applied (Partial Stimulus: Mask); third row: example of a stimulus to which the lower part of the face was covered by a white rectangular shape (Partial Stimulus: Half). Each stimulus begins with a neutral expression and arrive to express 100% of the target emotion in a 4-seconds video, in which in a second 25% of the final expression was added.

3.3 Procedure

The experimental procedure consisted of two phases. In Phase 1, participants viewed dynamic stimuli featuring emotional faces and were requested to categorize as soon as possible the emotion expressed (i.e., Emotion Categorization task). After a 1-minute break during which

participants were not engaged in any task, Phase 2 began. During Phase 2 participants were presented with static neutral faces and were asked to indicate whether the person depicted had been already presented in Phase 1 (i.e., Identity Recognition task). Participants were randomly assigned to one of two groups. All participants were presented with the same set of Whole Stimuli, consisting of 20 No-Mask faces. However, the Partial Stimuli varied between groups. One group was presented with 20 Mask faces (No-Mask/Mask group: NMM), while the other group was presented with 20 Half faces (No-Mask/Half group: NMH).

We decided to divide the sample into two subgroups to avoid familiarity with the stimuli during Phase 2 and to obtain a certain number of repetitions in each condition.

Before the experiment, participants underwent a training session for both emotion categorization and identity recognition tasks, to familiarize themselves with the experimental procedure. The training session lasted approximately 10 minutes, and the stimuli used were distinct from those presented in the main tasks. Participants received feedback on accuracy at the end of each trial during the training session. The feedback was provided within the program E-Prime to help them understand the task requirements. The purpose of the trial session was to ensure participants, particularly older adults with lower educational levels, became familiar and comfortable with the task procedures. Participants were asked to complete the entire procedure in a solitary, noiseless room while sitting in front of a computer screen and maintaining approximately 60 cm from the screen. The research was conducted in Italy during the period of COVID-19 pandemic restrictions, between May and June 2021. As participants could not be physically invited to the laboratory, the study was conducted online using E-Prime Go (<https://pstnet.com/eprime-go/>). Participants were limited to utilizing a PC for their participation, and the utilization of smartphones or tablets was not allowed. Tasks and data collection (accuracy and response times from target onset) were controlled by E-Prime 3.0. The study was conducted following the principles of the Declaration of Helsinki, and it was approved by the Institutional

Review Board of Psychology of the Department of Psychological, Health and Territorial Sciences – University “G. d’Annunzio” of Chieti-Pescara (protocol number: IRBP/21019).

3.4 Phase 1: Emotion Categorization task

For the Emotion Categorization task, participants were instructed to observe dynamic stimuli consisting of human faces that began with a neutral expression and progressively displayed an emotional expression. They were asked to press the spacebar key as soon as they recognized the expressed emotion, with a maximum stimulus length of 4000 ms (Di Domenico et al., 2015). Following the spacebar press, participants were presented with a response screen containing five verbal labels representing five possible emotions (Happiness, Anger, Fear, Sadness, and Disgust) and asked to indicate the expressed emotion by pressing the number key corresponding to the selected emotion. This response screen was presented as soon as the spacebar was pressed, or after the 4 sec of video presentation. Participants in the NMM group were randomly presented with 20 No-Mask and 20 Mask stimuli, while participants in the NMH group were randomly shown 20 No-Mask and 20 Half stimuli.

Performances were operationalized with two scores: accuracy and response times (RTs). Accuracy in identifying emotion was computed as a ratio of correctly identified emotions to the total number of faces presented, with a range from 0 (no correct responses) to 1 (perfect accuracy). For the sake of interpretability, RTs were converted into percentage of morphing level required to correctly identify the emotion (range 0%-100%). Hence, a participant recognizing an emotion after 1500 ms obtained a score of 37.5% ($1500 \text{ ms} * 100 / 4000 \text{ ms}$). Participants not pressing the spacebar within the maximum time of 4000 ms obtained a morphing percentage of 100%. The morphing percentage was calculated only for correct answers.

3.5 Phase 2: Identity Recognition task

In Phase 2, each group was presented with a total of 80 photographs of neutral faces. Half of the stimuli was the neutral static version of the 40 stimuli presented in Phase 1 (i.e., Familiar Stimuli). The remaining 40 stimuli were not presented in Phase 1 (i.e., New Stimuli). Twenty familiar and 20 new stimuli were presented as Whole Stimuli, the remaining faces were presented as Partial Stimuli, maintaining the same occlusion type assigned in Phase 1. Specifically, participants in the NMM group were presented with masked faces, whereas participants in the NMH group were presented with half-covered faces. Only Old Stimuli were further subdivided into Congruent and Incongruent stimuli, with Congruent stimuli referring to those that are consistent with the version seen in Phase 1. Incongruent stimuli represented stimuli that were incongruent with the previously observed version: Partial (Whole) faces presented in Phase 1 were presented as Whole (Partial) faces in Phase 2. As a result, the set of 40 Familiar Stimuli was constituted by 10 Partial Congruent, 10 Partial Incongruent, 10 Whole Congruent, and 10 Whole Incongruent stimuli. Two stimuli for each of the five emotions showed in Phase 1 were presented in each cluster.

Participants were instructed to press either the ‘I’ key on the keyboard if they identified the identity of the face as new, or the ‘E’ key if they identified the identity of the face as familiar (i.e., already seen in Phase 1). Each stimulus had unlimited duration until ‘E’, or ‘I’ keys was pressed.

Performances were operationalized using the detection index (d'). The index quantifies the sensitivity in distinguishing between hits (old stimulus correctly detected) and false alarms (new stimulus wrongly detected as familiar faces), with the formula:

$$d' = z(\text{FA}) - z(\text{H})$$

where FA and H are the False Alarm and Hit rates, respectively. Thus, $z(\text{FA})$ and $z(\text{H})$ are

the z-scores that correspond to the right-tail p-values represented by FA and H. A higher d' value indicates greater sensitivity of the observer in discriminating between signal (H) and noise (FA), while a lower d' value indicates reduced discriminability (Stanislaw & Todorov, 1999). To calculate d' scores for each participant the number of Hits was categorized according to Type of Stimulus, Congruency, and Emotion expressed in Phase 1, with a maximum of 2 hits per category and the maximum number of False Alarms corresponds to the number of New Stimuli ($n = 40$) used in Phase 2. For example, if a participant correctly identified a stimulus as "old" that was originally presented as an angry face in a congruent condition and was covered during phase 1, this would be counted as a Hit within the 'Angry-Congruent-Covered' category.

3.6 Statistical Analyses

Independent t-tests were used to compare the two age groups (YA and OA) for socio-demographic characteristics and for the scores obtained from the questionnaires (Table 1).

For phase 1, two repeated-measures analyses of variance (ANOVAs) were performed on participants' accuracy and morphing percentage (obtained by RTs). The morphing percentage was calculated only for correct responses. Participants who did not correctly categorize at least one emotion in Phase 1 were excluded from the analysis, as this indicated a failure to engage with the task. This resulted in a reduced sample size of 52 YA ($M = 24.96$, $SD = 4.82$) and 29 OA ($M = 73.11$, $SD = 7.29$).

We initially conducted 2 (Stimulus type: Partial faces, Whole Faces) x 5 (Emotion: Happiness, Anger, Fear, Sadness, and Disgust) x 2 (Condition: NMM, NMH) x 2 (Age group: YA, OA) ANOVAs, with Condition and Age group as between-subjects factors and Stimulus type and Emotion as within-subjects factors. Results showed Condition (NMM, NMH) had no significant main effect and did not significantly interact with the other factors, except for the two-way interaction between Emotion and Condition on morphing percentage (for more details

see the Supplementary Table 1 and Supplementary Table 3). For this reason, and with the aim to simplify the results, ANOVAs were carried out excluding Condition and using the factors Stimulus type, Emotion, and Age group. This final three-way ANOVA allowed us to better focus on the main effects of interest.

In phase 2, a repeated-measure ANOVA on participants' d' scores were conducted, including Age group (YA, OA) as between-subjects factor, and using Stimulus type (Partial, Whole), Congruence (Congruent, Incongruent) and Emotion (Happiness, Anger, Fear, Sadness, and Disgust) as within-subject factors. It is worth noting that the Condition (NMM, NMH) was not included in the analysis, starting from the results of Phase 1 not revealing significant differences. This choice allowed us to have the same statistical design for both phases. Moreover, two participants were excluded from the analyses because they consistently pressed the same button throughout the entire duration of the task. As a result, the sample size was reduced to 60 YA ($M = 24.77$, $SD = 4.56$) and 49 OA ($M = 73.88$, $SD = 7.34$). All analyses were performed using Statistica software v. 12 (StatSoft, 2013) and when needed post-hoc comparisons were performed using Tukey HSD tests (significant threshold: $p < 0.05$).

4. Results

4.1 Phase 1: Emotion Categorization task

The ANOVA Age group x Stimulus type x Emotion carried out on accuracy scores revealed a significant main effect of the Age group, $F(1, 109) = 69.75$, $p < .001$, $\eta^2 = 0.39$, indicating that YA ($M = 0.87$, $SE = 0.01$) were more accurate than OA ($M = 0.69$, $SE = 0.02$) in emotion categorization. Stimulus type was also significant, $F(1, 109) = 223.17$, $p < .001$, $\eta^2 = 0.67$, showing higher accuracy for Whole faces ($M = 0.87$, $SE = 0.01$) compared to Partial faces ($M = 0.69$, $SE = 0.01$). Also Emotion was significant, $F(4, 436) = 50.97$, $p < .001$, $\eta^2 = 0.32$.

Post-hoc showed significant differences between Disgust, receiving the lowest accuracy scores, and all other emotions, all $ps < .001$. Moreover, while Anger and Sadness were not statistically different from each other, they statistically differed from Happiness and Fear (all $ps < .05$), which, in turn, were not statistically different from each other (Disgust ($M = 0.61$, $SE = 0.02$) < Anger ($M = 0.77$, $SE = 0.02$) = Sadness ($M = 0.80$, $SE = 0.02$) < Happiness ($M = 0.86$, $SE = 0.01$) = Fear ($M = 0.87$, $SE = 0.01$)).

The interaction between Stimulus type and Age group was significant, $F(1, 109) = 11.35$, $p = .001$, $\eta^2 = 0.09$. Post-hoc comparisons revealed that the impairment of occlusion was greater for OA ($p < .001$; mean difference = .21) than for YA ($p < .001$; mean difference = .13). The interaction between Emotion and Age group was also significant, $F(4, 436) = 2.92$, $p = .021$, $\eta^2 = 0.03$. Post-hoc analyses revealed that YA showed a lower accuracy for Disgust with respect to all the other emotions, all $ps < .001$. In OA there were significant differences among all emotions (all $ps < .01$), except between Happiness and Fear, which have the highest scores, and between Anger and Sadness. Disgust were categorized with the lowest accuracy compared to all the other emotions in OA, all $ps < .001$.

The interaction between Stimulus type and Emotion was significant, $F(4, 436) = 47.06$, $p < .001$, $\eta^2 = 0.30$. Post-hoc analyses showed higher accuracy for Whole compared with Partial stimuli in Happiness: $p < .001$, in Anger: $p = .003$, and in Disgust: $p < .001$.

Finally, the three-way interaction among Age group, Stimulus type and Emotion was significant, $F(4, 436) = 6.19$, $p < .001$, $\eta^2 = 0.05$ (see Figure 2). Post-hoc comparisons and accuracy scores are reported in Supplementary Table 2. To summarize, YA had higher scores and statistically differed from OA for both Partial and Whole stimuli in all emotions (all $ps < .05$), except for whole stimuli expressing Happiness and partial stimuli expressing Disgust. Furthermore, a significantly decreased accuracy for Partial compared with Whole faces was evident for Happiness and Disgust in both YA and OA (YA, H: $p = .006$, all other $ps < .001$), but

for Anger this was significant only in OA, $p < .001$.

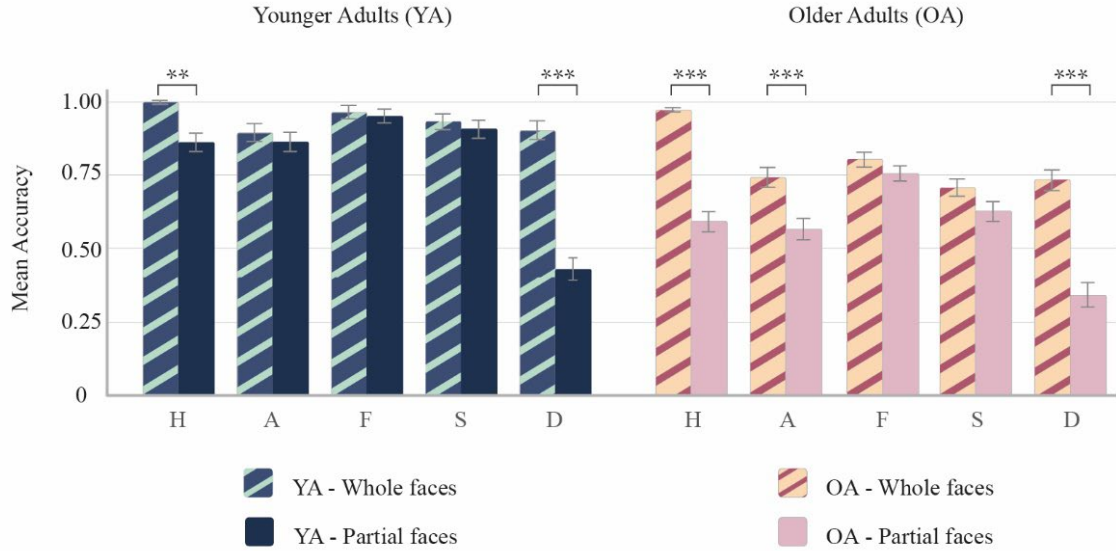


Figure 2. Three-way Interaction for the Repeated-Measures ANOVA on Mean Accuracy. Statistically significant differences in emotion recognition for Partial and Whole stimuli are highlighted, grouped by YA and OA. Error bars indicated Standard Errors. Note: *** = $p < .001$; ** = $p < .01$.

Results of the same three-way ANOVA on morphing percentage showed that the main effect of the Age group was significant, $F(1, 79) = 8.10$, $p = .006$, $\eta^2 = 0.93$, indicating that OA ($M = 86.10$, $SE = 2.79$) were slower to recognize the correct emotion than YA ($M = 76.20$, $SE = 2.08$). The main effect of Stimulus type was also significant, $F(1, 79) = 56.03$, $p < .001$, $\eta^2 = 0.41$, showing an slowdown in morphing percentage when the face was Partially covered ($M = 84.59$, $SE = 1.64$) compared to when it was Whole ($M = 77.70$, $SE = 1.94$). Emotion was significant, $F(4, 316) = 29.18$, $p < .001$, $\eta^2 = 0.27$, and post-hoc analyses revealed that Happiness and Fear were recognized more rapidly compared to Anger, Sadness and Disgust (all $ps < .001$; Happiness ($M = 75.58$, $SE = 2.03$) = Fear ($M = 77.37$, $SE = 2.26$) < Anger ($M = 83.65$,

SE = 1.81) = Sadness (M = 85.58, SE = 1.51) = Disgust (M = 83.55, SE = 1.73)).

The two-way interaction between Emotions and Age group was significant, $F(4, 316) = 3.20$, $p = .0135$, $\eta^2 = 0.04$. Post-hoc analyses showed that OA had higher scores than YA for all emotions (all $ps. < .005$), except for Happiness. Furthermore, in YA the morphing percentage were lower for Happiness and Fear compared to Anger, Sadness, and Disgust, all $ps. < .001$. In OA group, Happiness received the lowest score and differed significantly from Anger, Sadness and Disgust, all $ps. < .001$, and Fear statistically differ from Sadness, $p = .008$.

The two-way interaction between Stimulus type and Emotion was significant, $F(4, 316) = 35.53$, $p < .001$, $\eta^2 = 0.31$ (see Figure 3). All post-hoc analyses and morphing percentages can be found in the Supplementary Table 4. To summarize, post-hoc analysis revealed that Happiness, Sadness, and Disgust in the Whole versions statistically differed and were recognized faster compared to their partially covered versions (all $ps. < .001$). However, Anger and Fear are not statistically different between the two versions. Finally, the three-way interaction effect between Stimulus Type, Emotions, and Age Group was not significant, $F(4, 316) = 1.15$, $p = .335$.

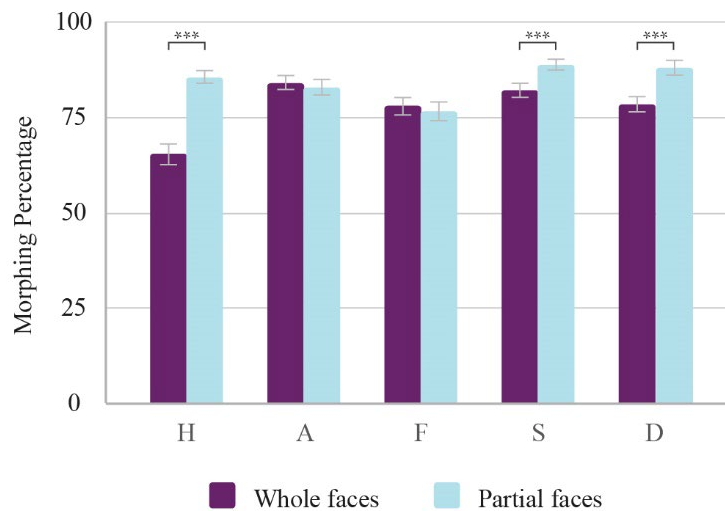


Figure 3. Interaction Between Emotion and Stimulus Type for the Repeated-Measures

ANOVA on Morphing Percentage. Note. Error bars indicated standard errors. * = $p < .05$, ** = $p < .01$

4.2 Phase 2: Identity Recognition task

Results of the ANOVA carried out by using d' scores as dependent variable showed that the main effect of Age group was not significant, $F(1, 107) = 1.02$, $p = .316$, $\eta^2 = 0.01$, but Stimulus type was significant, $F(1, 107) = 17.84$, $p < .001$, $\eta^2 = 0.14$, and it showed a higher d' scores in recognizing Partial ($M = 0.71$, $SE = 0.04$) compared to Whole stimuli ($M = 0.60$, $SE = 0.04$). The main effect of Congruence was significant, $F(1, 107) = 38.06$, $p < .001$, $\eta^2 = 0.26$, showing a higher d' scores for Congruent ($M = 0.71$, $SE = 0.04$) than Incongruent stimuli ($M = 0.59$, $SE = 0.04$). The main effect of Emotion was significant, $F(4, 428) = 3.05$, $p = .017$, $\eta^2 = 0.03$. Post-hoc analyses revealed that Disgust, with the highest d' score, was statistically different from Sadness, with the lowest d' score, $p = .012$ (Disgust: $M = 0.70$ $SE = 0.04$; Fear: $M = 0.68$ $SE = 0.04$; Anger: $M = 0.62$ $SE = 0.04$; Sadness: $M = 0.61$ $SE = 0.04$; Happiness: $M = 0.64$ $SE = 0.04$).

The interaction between Emotion and Age group was significant, $F(4, 428) = 2.87$, $p = .023$, $\eta^2 = 0.03$. In YA, d' score for Disgust was significantly higher than for Sadness, $p = .003$. However, no significant differences were found between OA and YA performances across emotions, all $ps > .138$.

The interaction between Stimulus type and Congruence was significant, $F(1, 107) = 21.75$, $p < .001$, $\eta^2 = .17$. Post-hoc analyses indicated that Incongruent Whole faces (faces that were Whole in Phase 1 but presented as Partial in Phase 2) were identified with greater difficulty compared to the other three conditions, all $ps < .001$.

Stimulus type interacted also with Emotion, $F(4, 428) = 10.42$, $p < .001$, $\eta^2 = .09$, revealing that the Partial version of Anger and Fear were identified with higher d' scores compared to their whole visible versions, all $ps < .001$.

The three-way interaction among Stimulus type, Congruence, and Emotion was significant, $F(4, 428) = 6.51$, $p < .001$, $\eta^2 = .06$ (see Figure 4), and post-hoc analyses and d' scores can be found in the Supplementary Table 5. To summarize, results revealed that Congruence generally did not affect d' scores of participants during the recognition of Partial stimuli expressing different emotions, whereas with Whole faces, participants showed higher d'

scores for recognizing Congruent stimuli expressing Happiness and Disgust, compared to both Congruent stimuli expressing Sadness, Anger, Fear, and all Incongruent conditions, all p s. < .017. Other interactions among factors were not significant.

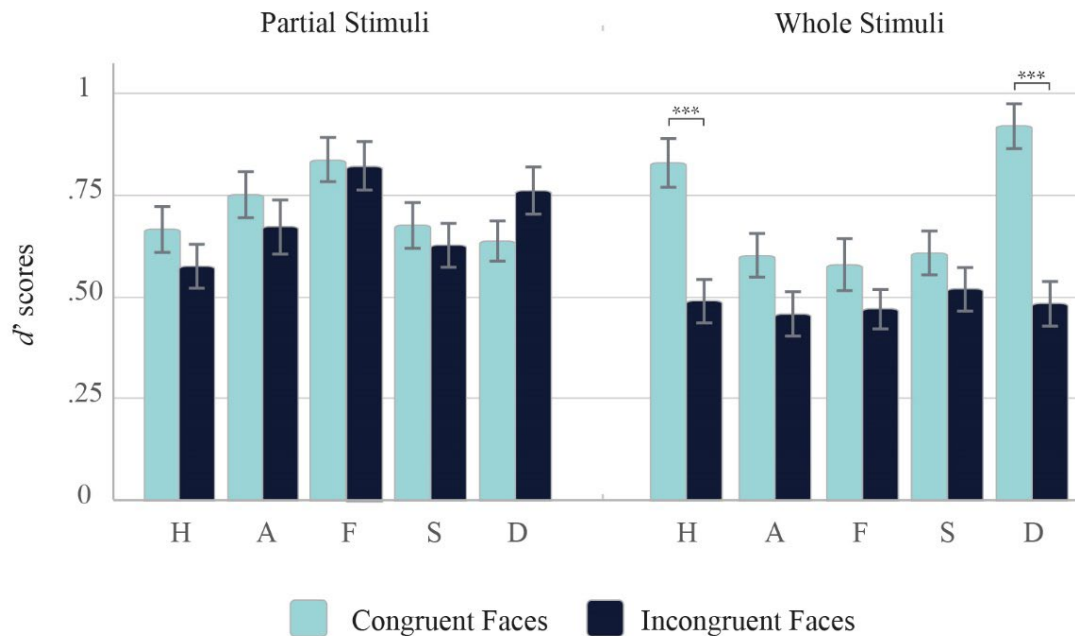


Figure 4. Three-way Interaction Among Stimulus Type, Congruence and Emotion in the Repeated-Measures ANOVAs on d' scores. Note. Error bars indicated Standard Errors. *** = p < .001

5. Discussion

This study had a dual purpose: to investigate age differences in emotion detection (phase 1) and to investigate identity recognition (phase 2) when faces were partially covered. We introduced age-related differences in the recognition of occluded faces using different types of coverings (masked and half-covered faces), and - differently from the majority of previous studies - occluded faces used for emotion recognition were dynamic, providing a more ecological contribution in this domain (Hayes et al., 2020). In both tasks we expected an overall higher

performance by younger compared to older adults, with a possible exception of positive emotional expression in phase 1, in which an age-related positivity effect was expected. Moreover, in both tasks we also investigated whether and to which extent facial occlusion affected the performance. This latter point was further investigated by using both an ‘ecological’ occlusion constituted by surgical mask, and an experimental occlusion created by presenting half faces. The first result emerged in the perceptual task is that the specific type of occlusion did not affect the result. In contrast to previous evidence (Grahlow et al., 2022), the specific type of occlusion did not affect performance in our perceptual task. One possible explanation is that our data were collected during the COVID-19 pandemic, and participants’ daily exposure to surgical masks may have modulated their processing of masked faces (Prete et al., 2020). Nevertheless, this was not the case and the two age groups did not differ in the score obtained in the fear of COVID questionnaire (Di Crosta et al., 2020), indeed occlusion was not further considered in data analyses.

Results of phase 1, besides the expected overall better performance in younger compared to older participants, showed that the perception of occluded stimuli led to an overall decrease in accuracy scores regardless of age group. This effect was significant when stimuli expressed happiness, anger, and disgust, but it diminished for fear and sadness, for which scores not significantly differed from the recognition of emotions in whole faces. A possible explanation, consistent with previous studies employing various forms of occlusion, is that the eye region, which remains fully visible, provides the specific emotional cues necessary for the accurate recognition of fear and sadness (Blais et al., 2017; Fischer et al., 2012; Kret & De Gelder, 2012). Among the emotional expressions presented, disgust was recognized with greater difficulty by both age groups, in accordance with previous evidence (Carbon, 2020). Finally, the occlusion had a negative impact on the recognition of happiness and disgust in both younger and older adults, while it affected anger only in older participants. Facial covering leads to a misinterpretation of some specific emotions: for instance, in a previous study, happiness was

often confused with a neutral expression, while disgust was often confused with anger (Carbon, 2020). The overall impairment in emotion categorization in older individuals might be attributed to both a general cognitive decline and neuropsychological changes across ages (Ruffman et al., 2008). Indeed, older adults show increased difficulties in recognizing basic emotions, and neuropsychological findings suggest that these challenges may be linked to age-related volume reductions in temporal regions, including the amygdala and fusiform gyrus (Li et al., 2016; Liu et al., 2018; Petrovic et al., 2008; Ruffman et al., 2008).

Results on morphing percentage, in line with previous literature (Bennetts et al., 2022; McCrackin et al., 2021), revealed a slower processing speed for occluded faces regardless of age group. This result was true for happiness, disgust, and sadness, whereas for fear and anger response times were not modulated by occlusion. The rapid categorization of fear and anger, potentially facilitated by their adaptive values, suggests an evolutionary advantage in promptly responding to threatening stimuli, even when partially occluded (Cho et al., 2023; Mather & Knight, 2006; Rigoulot et al., 2011; Vuilleumier, 2005). Finally, in accordance with existing literature (Deary & Der, 2005; Lee et al., 2021), we also found slower responses in older compared to younger participants, and interactions revealed this difference was true for all emotional expressions, except for happiness, in which no age difference emerged. This result could be framed as due to the hypothesized positivity effect in aging, referring to a kind of ‘preference’ toward positively-valenced stimuli in older persons (Carstensen & Mikels, 2005; Di Domenico et al., 2015; La Malva et al., 2023; Prete et al., 2024). Older adults, indeed, perceive more positive affect in facial expressions compared to younger adults and we hypothesized this positivity bias could be responsible for the absence of the expected slower performance in older participants only in the case of the positive expression of happiness (Kellough & Knight, 2012; Ruffman et al., 2008).

In phase 2 age difference was explored in an identity recognition task. Surprisingly, age

did not affect the task as a main effect, and an unexpected higher performance for occluded stimuli compared to whole faces emerged. Previous studies have demonstrated that the typical age-related decline in episodic memory is, at least in part, dependent on the stimuli used (Carstensen & Turk-Charles, 1994; D'Argembeau & Van Der Linden, 2004). Emotionally stimuli, both positive and negative, tend to be better remembered by older adults compared to neutral stimuli (Di Domenico et al., 2015; Ebner & Johnson, 2009). Previous studies employing emotionally charged stimuli have found no differences between younger and older participants, suggesting that the relative salience of information, such as emotion, is independent of age (Carstensen & Turk-Charles, 1994; D'Argembeau & Van Der Linden, 2004; Denkinger & Kinn, 2018; Hargis & Castel, 2017; Kensinger et al., 2002), also considering a lower educational level in older adults compared to younger adults. Another possible explanation could be that older adults rely on compensatory strategies, such as increased top-down regulation or attentional control, to enhance emotion processing. This notion aligns with socioemotional selectivity theory, which suggests that older adults prioritize emotionally meaningful goals and may allocate cognitive resources accordingly (Carstensen et al., 2003). The only difference found here according to the age group concerns the interaction with emotions: younger participants exhibited better memory for faces displaying disgust compared to those expressing anger. In the literature, this effect is explained within an evolutionary perspective as a mechanism to protect against potential infectious diseases (Duesenberg et al., 2016; Fernandes et al., 2017; Schienle et al., 2021). Furthermore, congruent happy and disgusted faces presented without occlusion were recognized more easily than other congruent and incongruent stimuli. Besides the disgust memory bias mentioned above, the effect on happiness could be attributed to the fact that a configural view of the face facilitates the processing of positive emotions compared to negative ones (Xie & Zhang, 2016).

In addition, results revealed an unexpected higher performance for occluded stimuli compared to whole faces. This result provides support for the prominent theory suggesting that

emotion recognition and facial identity recognition are distinct processes (Bruce & Young, 2012; Haxby et al., 2000). Consequently, we can expect that emotion perception and identity recognition are differently affected by partial occlusion. Recent research suggests that a combination of internal and external features appears to impact the recognition of both familiar and unfamiliar faces (Abudarham & Yovel, 2019). Logan et al. (2017) have indeed demonstrated how the configural processing associated with viewing whole faces can negatively affect the extraction of individual features and, consequently, facial identity discrimination. Another study by Leder and Carbon (2005) reported that when observers familiarized with isolated facial features, recognition accuracy was significantly higher compared to features embedded within a complete facial context. This result is also in line with the effect of congruence: congruent faces were more easily discriminated compared to incongruent ones. It is now well-established that the way we perceive a face plays a significant role in enhancing subsequent recognition probabilities (Hancock et al., 2000; Light et al., 1979), even though faces are seen only once. The study by Ventura and colleagues (2023) demonstrated that when faces are partially occluded during the learning session, face discrimination performance increased compared to those learned without occlusion. However, unlike the previously cited study, our research allowed participants to control the duration of their exposure to the stimuli. This methodological difference could have influenced the results, as participants spent more time in processing the occluded faces compared to the whole faces (phase 1). This increased exposure time may have provided participants with additional information on occluded faces (half stimulus), which might facilitate the unexpected memory recognition performance. Indeed, results revealed a better performance for occluded faces than for not-occluded incongruent faces, reiterating the distinction between facial identity recognition and emotion detection.

When considering the current results, it is important to acknowledge some limitations.

Firstly, the complexity of interactions among the variables involved in the study could increase the difficulty of interpretation and it can reduce statistical power of the analysis. Another limitation is the use of a web-based platform due to COVID-19 restrictions, resulting in uncontrolled technical variables such as monitor size and refresh rate since participants completed the task on personal computers. Moreover, the online setting makes it difficult to ensure that participants were fully focused during the task, as potential distractions in their environment were not controlled. Additionally, we presented images of young and middle-aged faces as stimuli, despite our sample consisting of younger and older adults. This choice allowed us to control for the possible effect of age-related facial features on emotion and identity recognition, but future studies could benefit from facial stimuli that span the same age range as the participant sample to better understand how age-related changes in facial features affect recognition processes (e.g., a possible own-age bias (C. Fernandes et al., 2023). In the same line, also a possible effect of gender could be taken into consideration in following studies in this domain (Hoffmann et al., 2010). Moreover, our age groups represent two extremes of the adult lifespan, with the absence of a middle-aged comparison group limiting the interpretation of age-related trajectories. Potential cohort effects should be considered also, as generational differences might influence performance independently of age-related cognitive changes. Moreover, psychological questionnaires showed significantly higher negative mood in older compared with younger participants (as shown by PANAS-), and the possible effect of this result on participants' performance should be further explored in future studies, even if any differences emerged in depression (BDI-II) and in positive mood (PANAS+). Finally, to maintain the task in a limited time interval, only two stimuli per combination of main factors were presented. This issue can influence the solidity of our results and following studies should enhance stimuli repetition (and emotional expressions) to further validate the present findings.

6. Conclusions

The present study enhances our understanding of emotion processing and facial identity recognition in both younger and older individuals. Our results indicate that both groups showed lower performance for occluded stimuli, with older adults demonstrating greater difficulty in emotion categorization. However, age did not have an impact on performance in face recognition. Interestingly, we also found that occluded faces were better remembered than whole faces. By employing dynamic, our findings provide ecologically valid insights into how these cognitive and affective mechanisms operate across the adult lifespan. The observed differences between younger and older adults not only shed light on age-related changes but also suggest the potential for adaptive strategies in later life. Future studies could explore the compensation strategies older adults employ to enhance their emotion-processing abilities, potentially analyzing the use of contextual cues or other non-verbal information. Finally, further investigations could more deeply explore how perceived emotion influences face identification and vice versa. In conclusion, the present study provides a robust starting point for further investigations that explore the complexities of emotion detection and face identification across different age groups, thus contributing to improving our understanding of the cognitive functions crucial for everyday social interactions.

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Appendix

Phase 1 - Emotion Recognition Task – Accuracy scores

Table S1. Results for the 2 (Stimulus type) x 5 (Emotions) x 2 (Condition) x 2 (Age Group) repeated-measures ANOVA on accuracy scores

	<i>F</i>	<i>p</i>	η_p^2
Condition	0.54	.462	.005
Age Group	67.70	< .001	.388
Stimulus type	217.94	< .001	.671
Emotions	51.67	<.001	.326
Condition*Age Group	0.26	.610	.002
Condition*Stimulus type	0.00	.995	.000
Condition*Emotions	2.72	.029	.025
Age Group*Stimulus type	11.089	.001	.094
Age Group*Emotions	2.74	.028	.025
Stimulus type*Emotions	46.79	< .001	.304
Condition*Age Group*Stimulus type	0.01	.946	.000
Condition*Age Group*Emotions	0.25	.912	.002
Age Group*Stimulus type*Emotions	6.02	< .001	.053
Condition*Stimulus type*Emotions	1.85	.118	.017
Stimulus Type*Emotions*Condition*Age Group	0.64	.632	.006

Note: **Condition:** NoMask-Mask vs. NoMask-Half; **Age Group:** Younger Adults vs. Older Adults; **Stimulus Type:** Partial Faces vs. Whole Faces; **Emotions:** Happiness (H), Anger (A), Fear (F), Sadness (S) and Disgust (D).

Table S2. Mean accuracy scores and post-hoc analyses for the three-way interaction effect in the 2 (Age Group) x 5 (Emotion) x 2 (Stimulus type) repeated-measures ANOVA

	Age Group	Stimulus type	Emotion	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
<i>M</i> (<i>SE</i>)				<i>1.00</i> (.01)	<i>0.90</i> (.03)	<i>0.97</i> (.02)	<i>0.93</i> (.03)	<i>0.91</i> (.03)	<i>0.86</i> (.03)	<i>0.86</i> (.03)	<i>0.95</i> (.02)	<i>0.91</i> (.03)	<i>0.43</i> (.03)	<i>0.98</i> (.01)	<i>0.75</i> (.03)	<i>0.81</i> (.03)	<i>0.71</i> (.03)	<i>0.74</i> (.04)	<i>0.60</i> (.03)	<i>0.57</i> (.04)	<i>0.76</i> (.03)	<i>0.63</i> (.03)	<i>0.35</i> (.04)
1	YA	Whole Faces	H		.179	.999	.908	.317	.007	.007	.999	.403	<.001	.999	<.001	.002	<.001	<.001	<.001	<.001	<.001	<.001	<.001
2	YA	Whole Faces	A			.851	.999	.999	.999	.999	.974	.999	<.001	.972	.069	.863	.004	.033	<.001	<.001	.179	<.001	<.001
3	YA	Whole Faces	F				.999	.948	.179	.179	.999	.974	<.001	.999	<.001	.034	<.001	<.001	<.001	<.001	.001	<.001	<.001
4	YA	Whole Faces	S					.999	.851	.851	.999	.999	<.001	.999	.003	.276	<.001	.001	<.001	<.001	.012	<.001	<.001
5	YA	Whole Faces	D						.999	.999	.995	.999	<.001	.992	.038	.753	.002	.017	<.001	<.001	.109	<.001	<.001
6	YA	Partial Faces	H							.999	.403	.999	<.001	.593	.425	.999	.059	.272	<.001	<.001	.688	<.001	<.001
7	YA	Partial Faces	A								.403	.999	<.001	.593	.425	.999	.059	.272	<.001	<.001	.688	<.001	<.001
8	YA	Partial Faces	F									.999	<.001	.999	<.001	.083	<.001	<.001	<.001	<.001	.002	<.001	<.001
9	YA	Partial Faces	S										<.001	.996	.027	.687	.001	.012	<.001	<.001	.083	<.001	<.001
10	YA	Partial Faces	D											<.001	<.001	<.001	<.001	<.001	.038	.200	<.001	.002	0.895
11	OA	Whole Faces	H												<.001	.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001
12	OA	Whole Faces	A													.985	.999	.999	.006	<.001	.999	.157	<.001
13	OA	Whole Faces	F														.499	.932	<.001	<.001	.999	<.001	<.001
14	OA	Whole Faces	S															.999	.157	.018	.998	.804	<.001
15	OA	Whole Faces	D																.018	.001	.999	.301	<.001
16	OA	Partial Faces	H																	.999	.001	.999	<.001
17	OA	Partial Faces	A																		<.001	.985	<.001
18	OA	Partial Faces	F																			.046	<.001
19	OA	Partial Faces	S																				<.001
20	OA	Partial Faces	D																				<.001

Phase 1 - Emotion Recognition Task – Percentage of Morphing

Table S3. Results for the 2 (Stimulus type) x 5 (Emotions) x 2 (Condition) x 2 (Age Group) repeated-measures ANOVA

	<i>F</i>	<i>p</i>	η_p^2
Condition	0.551	.460	.007
Age Group	8.150	.006	.096
Stimulus type	55.048	<.001	.417
Emotions	29.279	<.001	.275
Condition*Age Group	.015	.904	.000
Condition*Stimulus type	1.869	.176	.024
Condition*Emotions	3.439	.009	.043
Age Group*Stimulus type	1.552	.217	.020
Age Group*Emotions	2.830	.025	.035
Stimulus type*Emotions	34.294	<.001	.308
Condition*Age Group*Stimulus type	.075	.785	.001
Condition*Age Group*Emotions	1.536	.191	.020
Age Group*Stimulus type*Emotions	1.146	.335	.015
Condition*Stimulus type*Emotions	1.819	.125	.023
Stimulus Type*Emotions*Condition*Age Group	1.859	.118	.024

Note: **Condition:** NoMask-Mask vs. NoMask-Half; **Age Group:** Younger Adults vs. Older Adults; **Stimulus Type:** Partial Faces vs. Whole Faces; **Emotions:** Happiness (H), Anger (A), Fear (F), Sadness (S) and Disgust (D).

Table S4. Morphing percentage and post-hoc analyses for the two-way interaction effect in the 2 (Stimulus type) x 5 (Emotion) repeated-measures ANOVA

	Stimulus type	Emotion	1	2	3	4	5	6	7	8	9	10
<i>M</i> (<i>SE</i>)			65.44 (2.73)	84.26 (1.83)	78.04 (2.29)	82.21 (1.85)	78.56 (1.99)	85.73 (1.67)	83.03 (2.04)	76.70 (2.46)	88.96 (1.40)	88.53 (1.95)
1	Whole faces	H		<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001
2	Whole faces	A			<.001	.840	.004	.916	.995	<.001	.017	<.011
3	Whole faces	F				.083	.999	<.001	.009	.998	<.001	<.001
4	Whole faces	S					.395	.069	.999	.005	<.001	<.001
5	Whole faces	D						<.001	.086	.878	<.001	<.001
6	Partial faces	H							.343	<.001	.550	.463
7	Partial faces	A								<.001	<.001	<.001
8	Partial faces	F									<.001	<.001
9	Partial faces	S										.999
10	Partial faces	D										

Note: **Stimulus Type:** Partial Faces and Whole Faces; **Emotions:** Happiness (H), Anger (A), Fear (F), Sadness (S) and Disgust (D).

Phase 2 - Identity Recognition Task – d' scores

Table S5. d' scores and post-hoc analyses for the three-way interaction effect in the 2 (Congruence) x 5 (Emotion) x 2 (Stimulus type) repeated-measures ANOVA

Stimulus type		Congruence	Emotion	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
<i>M (SE)</i>				<i>0.67</i> <i>(.06)</i>	<i>0.68</i> <i>(.06)</i>	<i>0.75</i> <i>(.06)</i>	<i>0.84</i> <i>(.05)</i>	<i>0.64</i> <i>(.05)</i>	<i>0.58</i> <i>(.05)</i>	<i>0.63</i> <i>(.05)</i>	<i>0.67</i> <i>(.07)</i>	<i>0.83</i> <i>(.06)</i>	<i>0.76</i> <i>(.06)</i>	<i>0.83</i> <i>(.06)</i>	<i>0.61</i> <i>(.05)</i>	<i>0.61</i> <i>(.05)</i>	<i>0.58</i> <i>(.06)</i>	<i>0.92</i> <i>(.06)</i>	<i>0.50</i> <i>(.05)</i>	<i>0.52</i> <i>(.05)</i>	<i>0.46</i> <i>(.05)</i>	<i>0.47</i> <i>(.05)</i>	<i>0.49</i> <i>(.05)</i>
1	Partial Faces	Congruent	H		.999	.992	.351	.999	.997	.999	.999	.426	.969	.283	.999	.999	.997	.002	.283	.669	.098	.131	.283
2	Partial Faces	Congruent	S			.999	.506	.999	.984	.999	.999	.588	.992	.426	.999	.999	.984	.005	.173	.506	.052	.072	.173
3	Partial Faces	Congruent	A				.999	.946	.224	.811	.999	.999	.999	.999	.506	.588	.224	.351	.001	.012	<.001	<.001	.001
4	Partial Faces	Congruent	F					.173	.003	.072	.506	.999	.999	.999	.017	.025	.003	.992	<.001	<.001	<.001	<.001	<.001
5	Partial Faces	Congruent	D						.999	.999	.999	.224	.868	.131	.999	.999	.999	.001	.506	.868	.224	.283	.506
6	Partial Faces	Incongruent	H							.999	.984	.005	.131	.002	.999	.999	.999	<.001	.997	.999	.946	.969	.997
7	Partial Faces	Incongruent	S								.999	.098	.669	.052	.999	.999	.999	<.001	.744	.969	.426	.506	.744
8	Partial Faces	Incongruent	A									.588	.992	.426	.999	.999	.984	.005	.173	.506	.052	.072	.173
9	Partial Faces	Incongruent	F										.999	.999	.025	.037	.005	.984	<.001	<.001	<.001	<.001	<.001
10	Partial Faces	Incongruent	D											.999	.351	.426	.131	.506	.001	.005	<.001	<.001	.001
11	Whole Faces	Congruent	H													.012	.017	.002	.997	<.001	<.001	<.001	<.001
12	Whole Faces	Congruent	S														.999	.999	<.001	.946	.999	.744	.811
13	Whole Faces	Congruent	A															.999	<.001	.913	.997	.669	.744
14	Whole Faces	Congruent	F															<.001	.997	.999	.946	.969	.997
15	Whole Faces	Congruent	D																<.001	<.001	<.001	<.001	<.001
16	Whole Faces	Incongruent	H																	.999	.999	.999	.999
17	Whole Faces	Incongruent	S																		.999	.999	.999
18	Whole Faces	Incongruent	A																			.999	.999
19	Whole Faces	Incongruent	F																				.999
20	Whole Faces	Incongruent	D																				.999

Note: **Congruence:** Congruent and Incongruent faces **Stimulus Type:** Partial Faces and Whole Faces; **Emotions:** Happiness (H), Anger (A), Fear (F), Sadness (S) and Disgust (D).

CHAPTER 2: Detecting implicit and explicit facial emotions at different ages

Chapter 1 demonstrated that aging can reduce accuracy in emotion detection, particularly under challenging conditions like facial occlusion. However, their ability to recognize previously encountered faces remained unaffected, suggesting a dissociation between emotion processing and facial identity recognition. This illustrates the multifaceted influence of aging on distinct components of facial perception and underscores the importance of dynamic and contextually rich stimuli in capturing these processes.

Chapter 2 sought to delve deeper into the mechanisms underlying emotional perception in aging, focusing on the cortical and subcortical routes involved in processing facial expressions. Specifically, it will examine how older and younger adults process emotional stimuli presented in High Spatial Frequency (HSF), Low Spatial Frequency (LSF), and hybrid formats, including the impact of face inversion on these processes. By linking this work to prior research on emotion and identity recognition, the study aimed to address an important question: do aging-related changes in emotional perception extend to the fundamental neural pathways that process these stimuli? This investigation not only complements earlier findings but also provides critical insights into the broader impacts of aging on the brain's ability to decode and respond to emotionally salient cues.

1. Introduction

Facial emotions constitute the most critical cue in non-verbal communication, so two different cerebral routes have evolved to specifically cope with their analysis (LeDoux, 1996): the cortical route includes the Fusiform Face Area and other temporal and frontal regions, and it

is responsible for detailed, conscious, but relatively slow processing of facial stimuli; the subcortical route includes the amygdala, the pulvinar and the superior colliculus (Morris et al., 1999) and it is responsible for a fast but unconscious analysis (Johnson, 2005). Different studies revealed that each route is specialised in encoding specific features of the stimuli, with facial sex and identity preferentially processed by the cortical route, primarily based on the analysis of the High Spatial Frequencies (HSF) of the stimulus, and with emotional expressions preferentially processed through the subcortical route, which is primarily based on the analysis of the Low Spatial Frequencies (LSF) of the image (Lacroix et al., 2021; Vuilleumier et al. 2003; Williams et al. 2004). Interestingly, some evidence also suggests an association between different ranges of spatial frequencies and specific emotional expressions (Cassidy et al., 2021; Kumar and Srinivasan, 2011), making the field of the cortical/subcortical correlates of facial expressions even more complex. A crucial question often overlooked in this domain is the role of ageing and the possible changes in the lifespan concerning the role of the two cerebral routes during the processing of emotional stimuli. In the visual domain, the importance of the LSF (vs. HSF) has already been demonstrated in the foetus (Reid et al., 2017) and in newborns (Johnson, 2005). Still, it has also been found that in infants, emotional processing seems to be mainly based on the HSF (van den Boomen et al. 2019). However, contrasting evidence has been found (Pellicano and Rhodes, 2003), showing a non-linear relationship between age and the role of different SF/global vs local analysis in emotion detection. In this context, little is known about the possible effects of ageing: for instance, it has been found that older participants show a decrease in performance, compared to younger participants, specifically for HSF scenes (no difference emerged for LSF images), in an indoor vs outdoor categorization task (Ramanoël et al., 2015), but also that the global analysis of faces does not change across ages (Boutet and Faubert, 2006). Importantly, regarding emotions, a “positivity bias” has been widely documented in older adults (Mammarella et al., 2016a, 2017b; Reed et al., 2014). This bias consists of a lower impact of negative information on attention and memory processes in older adults than in younger adults

(Mammarella et al., 2016b; Mather, 2016; Mather and Knight, 2005), with less accurate performance in recalling negative events (Charles, 2010; Ceccato et al., 2022). This bias has been explained as due to the fact that when the temporal horizon of persons is limited, they would try to avoid negative emotions and would be strongly oriented toward positive experiences (Carstensen et al., 2006; Fusi et al., 2022; Cannito et al., 2021): this would happen in ageing when residual life duration is usually perceived as progressively limited (Ceccato et al., 2021, 2023). This positivity bias has been recently confirmed with surprised faces, considered ambiguous in valence (Barber et al., 2022). The authors found that older adults judged LSF and HSF surprised faces less negatively than younger adults. They proposed that, with ageing, a weaker activity of the subcortical route makes the cortical activity more influential in driving the response, which shows the expected positivity bias due to top-down cognitive control. This idea has been recently confirmed in a neuroimaging study showing that the positivity bias in older adults might be related to stronger activity in prefrontal areas (cortical route) and in reduced spontaneous activity of the amygdala (subcortical route), which is deactivated through a top-down cortical-subcortical neural pathway (Petro et al., 2021).

In this domain, “hybrid faces” constitute an interesting tool to investigate the relationship between SF and emotion processing through the two cerebral routes: they are created by superimposing the image of an emotional face filtered at LSF to the image of the same face with a neutral pose filtered at HSF. In this way, it is possible to investigate how the subcortical route (emotions shown in LSF) and the cortical route (neutral expression shown in HSF) work and how the brain processes the contrasting information in the same image. Hybrid stimuli were initially proposed by Schyns and Oliva (1994) and then they were modified and differently proposed by Laeng and colleagues (Laeng et al., 2010): in their version, a hybrid stimulus contains an emotional image filtered at 1-to-6 cycles per image (cpi), which is superimposed to the image of the same actor expressing a neutral pose and filtered at middle and high spatial frequencies (7–178 cpi). By using this set of stimuli, Laeng and colleagues (2010) showed that

even if participants were not able to explicitly label the emotions hidden in the LSF of hybrid stimuli (i.e., all stimuli were labelled as “neutral”), hybrid faces containing happy expressions were systematically judged as more friendly than those containing angry expressions. The authors concluded that the activity of the subcortical route is effectively involved in the unconscious processing of emotions, leading to an implicit modulation of emotional judgments. This speculation was also supported by the evidence that, differently from healthy controls, a patient with a lesion in the subcortical route (including the amygdala) did not show the expected friendliness judgment modulation according to the LSF of hybrid stimuli (Laeng et al., 2010). Starting from this last evidence, several further studies exploited the same hybrid stimuli as those used by Laeng et al. (2010) to investigate subliminal emotion processing, both at a behavioural (Prete et al., 2014, 2015b, 2018c) and electrophysiological level (Laeng et al., 2013; Prete et al., 2015a, 2019), confirming the implicit modulation of emotional processing through the LSF of the images (Neta et al., 2021). The advantage of such a category of stimuli in the study of subliminal emotions is that they can be presented for a long time, thus avoiding the need for a very brief presentation (i.e., tachistoscopic paradigm; e.g., Wang et al., 2021). They ensure that the emotional content remains under the level of awareness, given the possibility to indirectly measure the activation of the subcortical route.

Furthermore, besides being associated with emotional processing, the LSF of the image are also related to the global analysis of the stimuli (e.g., spatial orientation), as opposed to the HSF, mainly involved in the processing of local elements (e.g., details of a specific face). The well-known “face-inversion effect”, namely the systematic decrement in the ability to process facial details (local elements) when faces are rotated 180° about their vertical axis (Diamond and Carey, 1986), confirms that local (e.g., mouth and eyes) and global (orientation) analysis of faces are distinctive processes (Psalta et al., 2014). It has been shown that emotional expressions are related to the global processing of stimuli (Psalta and Andrews, 2014). Thus, we can conclude that facial emotions are rapidly processed by the subcortical route, which is responsible for an

implicit, fast, and unconscious analysis, based on the global processing of the percept, mainly based on the LSF.

Starting from this complex frame, the present study aims to shed light on the functioning of the subcortical route in ageing, investigated by exploiting hybrid faces as in previous studies (Laeng et al., 2010; Prete et al., 2014, 2015b, 2018; Laeng et al., 2013; Prete et al., 2015a, 2019). Differently from previous evidence collected with hybrid stimuli, in which participants were asked to express a friendliness judgment, here a go/no-go task is used to quantify the explicit categorisation of emotional versus neutral faces presented as unfiltered (broadband), filtered at HSF, filtered at LSF and hybrid. Two age groups (younger and older adults) were tested in an emotional go/no-go task to directly compare the performance at different ages. Moreover, to further investigate the relationship between global/local analysis and the functioning of the subcortical/cortical route, all stimuli were presented in canonical (upright) and inverted orientation (upside-down). We asked participants to detect the emotional stimuli (go) and to avoid a response when neutral faces were presented (no-go). We expected a better performance in younger adults than older adults for faces filtered at LSF and hybrid (subcortical route) due to a weakening activity of the subcortical route in ageing (Barber et al., 2022; Petro et al., 2021). For the same reason, a weaker performance was hypothesised in older compared to younger participants for stimuli presented upside-down (global analysis based on the LSF). Instead, an absence of age difference was expected for stimuli presented both unfiltered and filtered at HSF since these stimuli would activate the cortical route, which is supposed to be strongly active also in ageing (Petro et al., 2021). Finally, in accordance with the positivity bias, better performance in ageing was expected for positive (i.e., happy) than for negative (i.e., angry) facial expressions (Barber et al., 2022; Di Domenico et al., 2015; Mather, 2016). Data collected through a go/no-go emotional task were analysed to show how each of the factors manipulated in the study interacted with each other, and we expected younger participants to outperform older ones for LSF and hybrid stimuli, mainly when presented in inverted orientation, particularly with an

angry expression.

2. Materials and methods

2.1 Participants

Participants were contacted via social media messages and emails sent to university students, who were asked to also involve relatives and friends. Students were informed that, for whom would be interested in, the results collected for this study would be discussed together in classroom (they did not receive payment for participation). Exclusion criteria were explicitly stated in the initial messages, consisting in neurological and/or psychiatric conditions, as well as visual impairments. Considering possible dropout, which is high in online studies, we decided to stop the administration when at least 130 younger and 130 older participants completed the paradigm, with the aim to obtain a final sample of at least 100 participants in each age group. From the initial sample of 277 participants, 41 responders started the task online, but they did not complete the paradigm, 6 younger and 7 older participants were excluded from the analyses because their accuracy means were two standard deviations out than the total mean of their age group. A final sample of 223 participants was included in the analyses, divided into two groups: 112 younger adults (YA), including 79 females and 33 males, with an age between 18 and 35 years (mean age $\pm$ standard error: 24.27 ± 0.37 years old), including 10 left-handers, as self-reported; 111 older adults (OA), including 64 females and 47 males, with an age between 65 and 94 years (72.84 ± 0.71 years-old), including 2 self-reported left-handers. Prior the beginning of the task, all participants declared their handedness, to have normal or corrected-tonormal vision, as well the absence of neurological and/or psychiatric conditions. All were unaware of the purpose of the study.

2.2 Stimuli

Stimuli were created from photographs in the Karolinska Directed Emotional Faces

(Lundqvist et al., 1998), a database of faces in neutral and emotional poses. Photographs in frontal view of 15 female and 15 male faces in happy, angry, and neutral expressions were selected, converted into grey-scale images, measuring $5.2^\circ \times 5.3^\circ$ of visual angle (260×270 pixels) seen at a distance of 72 cm (see Fig. 1a). Then, all stimuli were filtered through MatLab software (Mathworks Inc., Natick, MA), obtaining one image filtered at low spatial frequency (LSF; 1–6 cycle per image: cpi; see Fig. 1b) and another image filtered at high spatial frequency (HSF; 7–128 cpi; see Fig. 1c). Experimental stimuli were constituted of unfiltered faces, faces presented at LSF, at HSF, and hybrid faces. Emotional hybrid faces were created by superimposing the LSF of an emotional face (either angry or happy) to the photograph in HSF of the same face with a neutral expression (see Fig. 1d). Hybrid neutral faces were presented unfiltered (i.e., neutral LSF was superimposed to neutral HSF, resulting in a neutral broadband image; see (Prete et al. 2018; Tommasi et al. 2021)).

2.3 Procedure

Once recruited, participants were invited to read and subscribe an informed content to take part in the study, and then to download on their PC an E-Prime Go auto-run script. At the beginning, they were instructed to carry out the task in isolation and in a dark and silent room, and to position the screen monitor at 72 cm from their face (auto-run did not work on tablets and

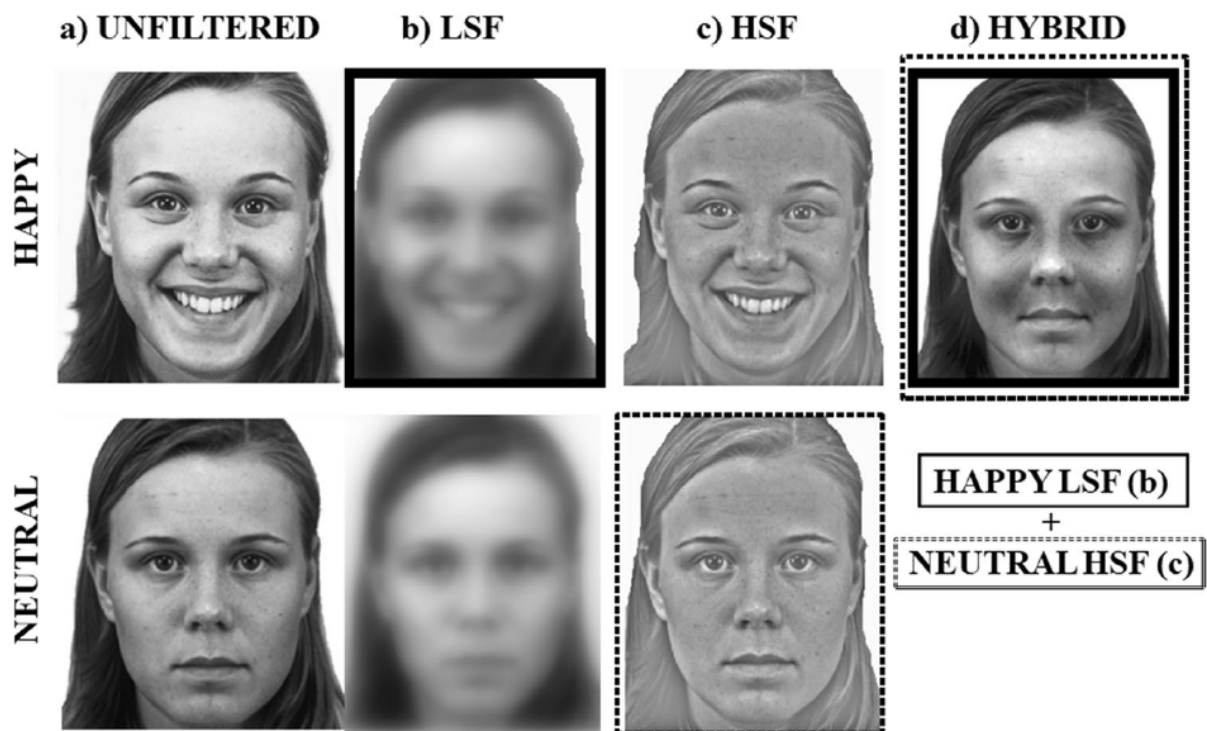


Fig. 1. Examples of happy (upper row) and neutral (lower row) faces presented as: **a)** unfiltered (e.g., original stimuli), **b)** filtered at Low Spatial Frequencies (LSF: 1–6 cpi), **c)** filtered at High Spatial Frequencies (HSF: 7–128 cpi), and **d)** hybrid faces, created by superimposing the LSF of an emotional face (in this case, happy LSF stimulus, black frame) to the HSF of the neutral expression of the same face (in this case, neutral HSF stimulus, dotted frame). Neutral hybrid faces were the same as neutral unfiltered stimuli (neutral LSF superimposed to neutral HSF).

The 240 stimuli were presented upright (canonical orientation) and upside-down (rotated 180° on the vertical axis) for a final set of 480 different trials in the Angry session and 480 different trials in the Happy session (no repetition of the same stimulus in the same orientation was included). Happy and angry expressions were presented in two different sessions to make the task easier especially for older participants, and for the same reason a Go/No-Go task was created, in order to have just one response key and a easy-to-be-remembered task (i.e., detect a target expression).

In each trial, after a fixation cross presented in the centre of the screen for 150 ms, a stimulus was presented for 2 s, during which the participant was required to give their response, otherwise the next trial started (after 2 s, which was a fixed presentation time). Participants were instructed to detect the target emotional expression, disregarding both filtering and spatial orientation, by pressing the key “m” on the keyboard as soon as an emotional face appeared (either angry or happy in the two separate sessions), otherwise they were asked to give no response when a neutral face was presented (with neutral stimuli constituting 50% of the trials; see Fig. 2). The presentation order of the trials was randomised within and across participants in each session. A set of 8 trials was presented before the beginning of the task to allow participants

to familiarise themselves with the procedure.

All participants had given informed consent to participate in the research. The procedure was carried out following the principles of the Declaration of Helsinki and was approved by the Institutional Review Board of Psychology of the [anonymized for review] (protocol number: [anonymized for review]). The paradigm lasted about 30 min and was shared and controlled by E-Prime-go software (Psychology Software Tools, Inc., Pittsburgh, PA).

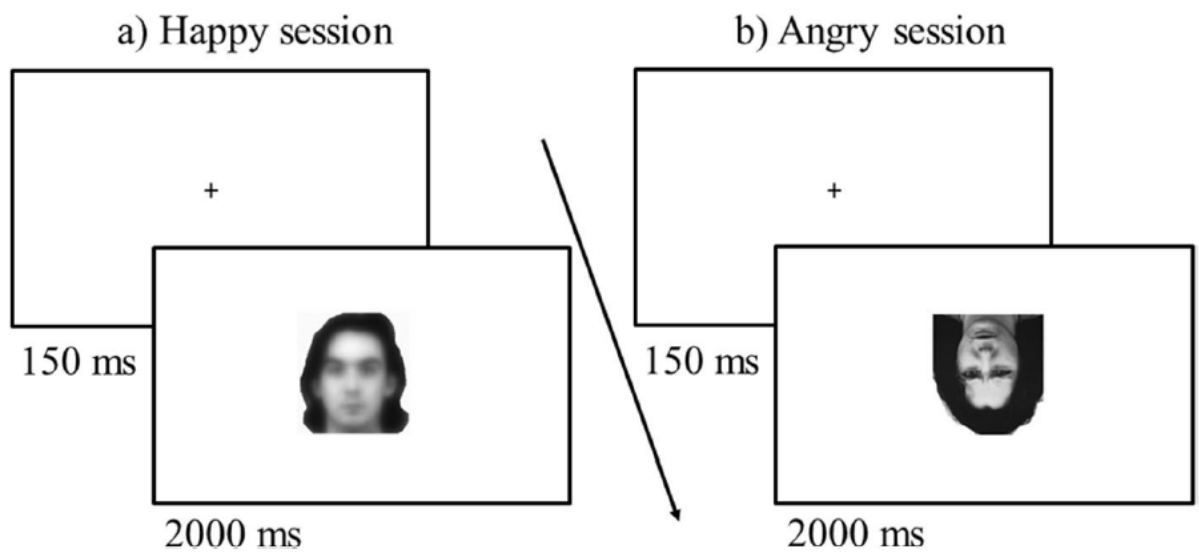


Fig. 2 Schematic representation of the two sessions of the paradigm: **a)** neutral face presented upright at LSF (example of a no-go trial); **b)** angry face presented upside-down unfiltered (example of a go trial).

2.4 Statistical analysis

Data were automatically recorded on the E-Prime Go server and were then downloaded and aggregated. For each participant, the proportion of false alarms (wrong detection of an emotional expression when a neutral stimulus was presented) was subtracted from the proportion of hits (correct detection of the emotional trials) to obtain the overall index of the performance Pr (i.e., $Pr = Hits - False\ alarms$; Snodgrass and Corwin, 1988). Data were analysed by using

Statistica software (StatSoft Inc., Version 7), employing a $2 \times 2 \times 2 \times 4$ analysis of variance (ANOVA), using Pr as the dependent variable, Group (YA, OA) as a between-subject factor, and Emotion (Angry, Happy), Orientation (Upright, Upside-down) and Filtering (Unfiltered, LSF, HSF, Hybrid) as within-subject factors. When needed, post-hoc comparisons were computed by using the Duncan test, and the significance threshold was set at $p = 0.05$.

3. Results

All results are reported in Table 1. Main effects were all significant: Group ($F(1, 221) = 40.021, p < 0.001, \eta^2_p = 0.153$) showed a better performance of YA (0.627 ± 0.013) compared to OA (0.521 ± 0.02); Emotion ($F(1, 221) = 191.01, p < 0.001, \eta^2_p = 0.464$) showed higher Pr scores for Happy (0.635 ± 0.013) than for Angry faces (0.514 ± 0.013); Orientation ($F(1, 221) = 116.88, p < 0.001, \eta^2_p = 0.346$) confirmed the expected better performance for Upright (0.604 ± 0.012) than for Upside-down presentation (0.544 ± 0.014). Also, Filtering was significant ($F(3, 663) = 2578.02, p < 0.001, \eta^2_p = 0.921$). Post-hoc comparisons revealed that Pr was lower for Hybrid (0.046 ± 0.007) compared to all of the other filtering conditions and for LSF (0.677 ± 0.017) compared to both HSF (0.782 ± 0.014) and Unfiltered (0.793 ± 0.014) stimuli ($p < 0.001$ for all comparisons).

The interaction between Group and Filtering ($F(3, 663) = 36.59, p < 0.001, \eta^2_p = 0.142$) confirmed all the above-mentioned post-hoc comparisons in both groups and also that YA performed better than OA in all filtering conditions (all $ps < 0.001$) except for hybrid stimuli, for which the comparison was not significant. Furthermore, the interaction between Group and Orientation ($F(1, 221) = 36.54, p < 0.001, \eta^2_p = 0.142$) confirmed a better performance for Upright than for Upside-down orientation in both groups ($p < 0.001$). Finally, it also revealed that the performance of YA was better than OA for both Upright and Upside-down orientations ($p < 0.001$).

The significant interaction between Emotion and Orientation ($F(1, 221) = 58.57, p <$

0.001, $\eta^2_p = 0.21$) confirmed a better performance for the Upright compared to the Upside-down condition with both Angry and Happy emotions, together with a better performance for Happy than for Angry faces presented both Upright and Upside-down (all $p < 0.001$). Emotion $\times$ Filtering interaction ($F(3, 663) = 60.43, p < 0.001, \eta^2_p = 0.215$), confirming higher Pr for Happy than for Angry faces in all filtering conditions, also showed that only for the Happy expression, the performance was significantly different between each filtering condition (Happy: Unfiltered $>$ HSF $>$ LSF $>$ Hybrid), but no difference emerged between Unfiltered and HSF for Angry expression (Angry: Unfiltered = HSF $>$ LSF $>$ Hybrid). Also, the Filtering $\times$ Orientation interaction was significant ($F(3, 663) = 80.21, p < 0.001, \eta^2_p = 0.27$), confirming a better performance for Upright than for Upside-down orientation in all filtering conditions (all $p < 0.001$), as well as a lower performance within each orientation for Hybrid than LSF, LSF compared to HSF, and for HSF than for Unfiltered stimuli (Unfiltered $>$ HSF $>$ LSF $>$ Hybrid; $p < 0.001$), except for the non-significant comparison between Unfiltered and HSF in the Upright orientation.

	<i>MS</i>	<i>F</i>	<i>p</i>	η^2_p
Group	9.963	40.021	< 0.001	0.153
Emotion	13.097	191.010	< 0.001	0.463
Emotion $\times$ group	0.020	0.291	0.590	0.001
Orientation	3.229	116.878	< 0.001	0.346
Orientation $\times$ group	1.009	36.539	< 0.001	0.142
Filtering	112.988	2578.019	< 0.001	0.921
Filtering $\times$ group	1.604	36.595	< 0.001	0.142
Emotion $\times$ Orientation	0.599	58.570	< 0.001	0.210
Emotion $\times$ orientation $\times$ group	0.133	13.032	0.0003	0.056
Emotion $\times$ filtering	0.918	60.427	< 0.001	0.215
Emotion $\times$ filtering $\times$ group	0.047	3.101	0.026	0.014
Orientation $\times$ filtering	0.632	80.214	< 0.001	0.266
Orientation $\times$ filtering $\times$ group	0.106	13.494	< 0.001	0.058
Emotion $\times$ orientation $\times$ filtering	0.219	32.844	< 0.001	0.129
Emotion $\times$ orientation $\times$ filtering $\times$ group	0.087	12.973	< 0.001	0.055

Table 1. Results of the $2 \times 2 \times 2 \times 4$ ANOVA (Group, Emotion, Orientation, Filtering) on the Pr score.

The three-way interaction among Group, Emotion, and Orientation ($F(1, 221) = 13.03, p < 0.001, \eta^2_p = 0.056$) showed that the performance of the YA group was better than that of the

OA group in all conditions and that in both groups the performance was better for Upright compared to Upsidedown orientation, except for YA in Happy condition which failed to reach significance (Upright vs Upside-down: $p = 0.058$). The significant interaction among Group, Emotion, and Filtering ($F(3, 663) = 3.10, p = 0.026, \eta^2_p = 0.014$) showed a better performance of YA compared to OA in all conditions ($p < 0.001$), except for Hybrid Angry and Hybrid Happy faces, in which comparisons were not significant. Furthermore, for both YA and OA groups and Angry and Happy stimuli, the performance was not different between Unfiltered and HSF stimuli. Still, it was higher in these conditions compared to the LSF and higher for the LSF compared to the Hybrid condition (i.e., Unfiltered = HSF > LSF > Hybrid), with this latter comparison being not significant only for YA with Happy faces. The interaction among Group, Orientation, and Filtering was significant ($F(3, 663) = 13.49, p < 0.001, \eta^2_p = 0.058$). Posthoc comparisons confirmed a better performance of the YA than the OA group in both orientations and for all Filtering conditions, except for Hybrid stimuli which did not reach statistical significance. Emotion, Orientation, and Filtering significantly interacted ($F(3, 663) = 32.84, p < 0.001, \eta^2_p = 0.13$), confirming Unfiltered > HSF > LSF > Hybrid for both Angry and Happy faces presented in Upright orientation, and only for Angry faces presented in Upside-down orientation. For Happy stimuli in Upside-down orientation, there was no difference between Unfiltered and HSF filtering (Unfiltered = HSF > LSF > Hybrid).

Finally, the interaction among all four factors was significant ($F(3, 663) = 12.97, p < 0.001, \eta^2_p = 0.055$). To better understand this four-way interaction, four different ANOVAs were carried out, one for each level of Filtering, using Group as the between-subject factor and Emotion and Orientation as within-subject factors. The interaction between Group, Emotion, and Orientation was significant for Unfiltered ($F(1, 221) = 37.41, p < 0.001, \eta^2_p = 0.14$; Fig. 3a) and for HSF stimuli ($F(1, 221) = 22.09, p < 0.001, \eta^2_p = 0.09$; Fig. 3b), but it was not significant for LSF stimuli (see Fig. 2c) and for Hybrid stimuli (Fig. 3d).

In both Unfiltered and HSF ANOVAs, post-hoc comparisons confirmed a better performance of the YA than the OA group for Happy faces presented both Upright and Upside-down and Angry faces Upside-Down. Moreover, in both ANOVAs, in all conditions and groups, the performance was better for Happy than Angry faces. Post-hoc tests in the Unfiltered ANOVA (Fig. 3a) showed that in the OA group, the performance was significantly better when Angry faces were presented Upright instead of Upside-down ($p < 0.001$). In the HSF ANOVA (Fig. 3b), post-hoc tests revealed that for the OA group, the performance was better for Upright compared to Upside-down orientation for both Angry ($p < 0.001$) and Happy faces ($p = 0.001$).

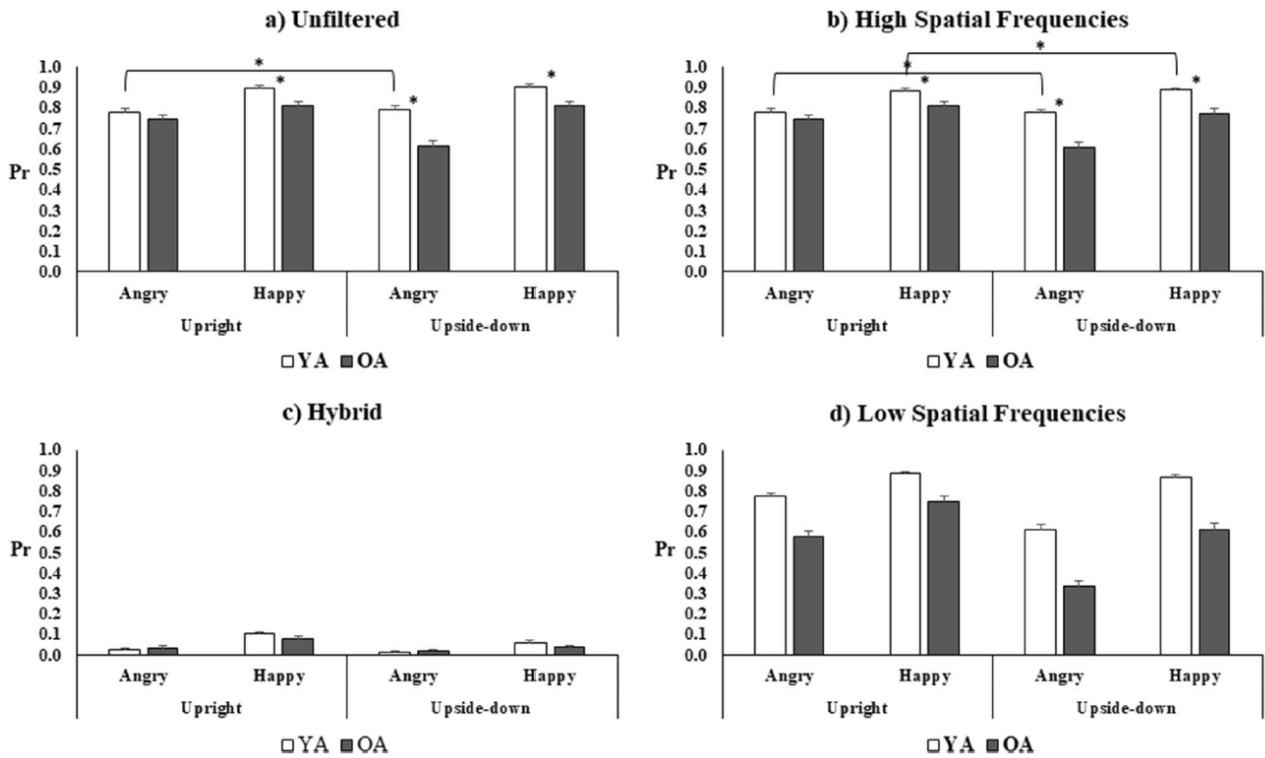


Fig. 3. Results of the four ANOVAs carried out on Pr scores, showing the interactions among Group (Younger Adults: YA, Older Adults: OA), Emotion (Angry, Happy), and Orientation (Upright, Upsidedown) for each filtering condition: **a)** Unfiltered, **b)** filtered at High Spatial Frequencies, **c)** hybrid, **d)** filtered at Low Spatial Frequencies. Panels **a)** and **b)** represent the significant interaction, whereas panels **c)**, **d)** show no significant interactions. Bars represent standard errors, and asterisks show significant post-hoc comparisons (to note that, even if not

showing by asterisks, all comparisons between Happy and Angry are significant for both Unfiltered and HSF conditions).

4. Discussion

The present study investigated the relationship between implicit vs. explicit emotion processing and ageing (Schiller et al., 2024). We exploited the spatial filtering technique to indirectly investigate the functioning of the subcortical route in subliminal emotion processing through a go/no-go emotional task. Starting from previous evidence (Petro et al., 2021), we expected that ageing would impair the subcortical route and it would enhance the functioning of the cortical route, leading to (i) a worse performance in detecting emotional faces in older compared to younger participants, when stimuli were presented at LSF and hybrid (with the emotional content presented in the LSF and hidden by a neutral expression superimposed at HSF). In contrast, we expected (ii) no difference between the two age groups for unfiltered stimuli and stimuli filtered at HSF because this processing would activate the cortical route, which is supposed to be strongly activated in ageing (Petro et al., 2021). Furthermore, we also expected that (iii) all stimuli presented rotated 180° about the vertical axis (i.e., upside-down) would lead to worse performance in general, with either a possible specific effect in ageing, due to the fact that face-inversion is based on a global analysis, which in turn should be based on the subcortical route; or a similar performance in the two age groups starting from other evidence suggesting that global analysis is intact in the elderly (Boutet and Faubert, 2006). Finally, (iv) starting from the positivity bias described in ageing (Barber et al., 2022; Carstensen et al., 2006; Charles, 2010; Mather, 2016; Mather and Knight, 2005; Reed et al., 2014), we expected a lower performance of older adults to be evident only for the negative emotion (i.e., anger), mainly when processed through the subcortical route (LSF and hybrids), but either no age difference or better performance in older adults compared to younger participants was hypothesised for the

positive emotion (i.e., happiness).

Results showed an overall better performance for younger compared to older participants, which would be due to a general perceptual and cognitive decline in ageing (Fisk and Warr, 1996; Meinhardt-Injac et al. 2014), as revealed by the analyses carried out on Pr, which is a synthetic and informative value in such a paradigm, being calculated as the difference between hits and false alarms (Snodgrass and Corwin, 1988). In this frame, it is useful to underline that only hits and false alarms were considered in the present study without considering response times, specifically due to the well-known slowdown in ageing (Ruffman et al., 2008). In fact, we did not required participants to respond as soon as possible (so that response times were not considered as dependent variable). Moreover, the go/no-go paradigm was chosen to favour the participation of older people, hypothesizing that only one response (and one response key) would be preferred to more complex response options, especially for people who are not confident with electronical devices. Nevertheless, a group difference in Pr scores emerged for unfiltered, LSF, and HSF stimuli, as revealed by the interaction between group and filtering, with only hybrid stimuli not showing a worse performance in older adults. This absence of age difference for hybrid faces seems to be due to a low performance by younger participants rather than to a high performance by older participants, and this can be attributable to the peculiar composition of hybrid stimuli: as specified above, in fact, in hybrid faces, the emotional content presented at LSF is “hidden” by the neutral content presented at HSF. Since the specific task used here is an “explicit” categorisation task (emotional vs neutral), we can speculate that the conscious output of the cortical route (neutral HSF) was predominant in driving the explicit response required, overriding the activity of the subcortical route (emotional LSF). In this context, the present results align with the pioneering evidence described by Laeng and colleagues with hybrid faces (Laeng et al., 2010), showing that participants labelled all hybrid emotional stimuli as neutral when an explicit categorisation was required. Coming back to our experimental hypotheses, we found support (i) for the absence of an age difference for hybrid stimuli, but we found support

neither for the expected absence of age difference for LSF stimuli, (ii) nor for the expected similar performance across different age groups for stimuli presented unfiltered and filtered at HSF. This pattern of results is not in line with the expected weaker activity in ageing, specifically for the subcortical route. Still, it seems to support a general worsening in emotion detection in ageing. Furthermore, interactions confirmed that the absence of age differences emerged for hybrid stimuli presented both with a happy and an angry expression (group $\times$ emotion $\times$ filtering) and for hybrid stimuli presented both upright and upside-down (group $\times$ orientation $\times$ filtering), confirming an overall inability to explicitly categorise the emotional content hidden in hybrid faces in a go/no-go task.

Concerning the third hypothesis, results confirmed the expected face-inversion effect (Prete et al., 2015c), but also, in this case, no age difference emerged, with worse performance for stimuli presented upside-down than upright in both younger and older participants, for both happy and angry faces, and in all filtering conditions. This result, confirming that faces are processed holistically, does not support a specific impairment for upside-down faces in ageing, confirming the evidence according to which global analysis of faces remains the same throughout the lifespan (Boutet and Faubert, 2006).

Lastly, a positivity bias specific to older participants was hypothesised (Barber et al., 2022; Mather, 2016): the present results confirmed a better performance for happy compared to angry faces, but (iv) no ageing effect was found since both groups showed a better performance with the positive than the negative emotion. This finding can be ascribed to a general facilitation often described for happiness compared to the other basic emotions (Leppänen and Hietanen, 2004). A peculiar interaction between emotion and filtering revealed that, while for happy faces the performance was statistically different among each level of filtering (e.g., unfiltered > HSF > LSF > hybrid), for angry faces there was no difference between LSF and hybrid stimuli. This pattern is in line with the idea that happiness is a “distal” emotion based on LSF processing,

whereas anger would be a “proximal” emotion based on the HSF (Smith and Schyns, 2009). Thus, only for happiness the performance was better for LSF alone than for the “mixed” (emotional and neutral) hybrid condition.

Finally, the interaction among all the factors clarifies and substantially confirms all the interactions discussed above. Four analyses were carried out to shed more light on these results, splitting data according to the specific filtering condition. Results confirmed no significant interaction among group, emotion, and orientation for hybrid stimuli and—surprisingly—for stimuli filtered at LSF. This evidence confirms that the present results do not support the hypothesized lower activity of the subcortical route in ageing because no age difference emerged in both the conditions in which LSF conveyed an emotional content (LSF and hybrid). The fact that such an age difference, with younger participants outperforming older participants, is present in both unfiltered and HSF conditions, suggests a stronger functioning of the cortical route in younger compared to older participants. Only in the unfiltered condition, the performance of the older adults did not differ for happy faces presented upright vs. upside-down, possibly showing a resistance to the faceinversion effect only for happiness, which remains the emotion leading to better performance. However, the fact that angry faces presented upright in both unfiltered and HSF conditions did not reveal age differences seems to confirm that when a “proximal” emotion is shown (HSF; (Smith and Schyns, 2009) and faces are presented in canonical orientation (upright), older participants show the same performance as younger ones, partially confirming the hypothesis of a preserved ability to process emotions by means of the cortical route.

The study contains some critical aspects that should be fully considered in future works. Primarily, the evidence collected here is an indirect measure of the functioning of the dual route model, indeed neuroscientific data must be collected to prove the activity of the cortical vs subcortical route at different ages. Furthermore, this is the first-time hybrid faces were administered to participants older than 65. Therefore, all data collected in previous research

involving young participants are considered reference data here, but no direct evidence exists about the cerebral processing of hybrid faces in ageing. This is also a strength of the work, but subliminal emotion processing of these stimuli in older adults, as shown with younger observers (Laeng et al., 2010; Prete et al. 2015a), should be proven. However, the fact that the hybrid condition is the only condition in which no difference emerges between the two age groups indirectly shows that these stimuli are processed similarly in younger and older adults. Another point to be stressed is the online administration of the paradigm. When images are filtered at different spatial frequencies, the exact distance the observer is positioned with respect to the stimulus is crucial for the exact range of SF viewed. Regarding this point, in the instructions given before the task, we specifically stressed the importance of maintaining the required distance from the screen, but it must be acknowledged that different the devices used prevent us to maintain a control over the specific features of the computer used (e.g., screen size, brightness and so on). Moreover, we recruited a large sample of participants to compensate for possible issues in this regard.

Finally, it must be highlighted that only one positive and one negative emotion were used in the present study, so the results are not generalisable to all emotions. We selected happiness and anger as they are the two facial expressions that received the most extreme friendliness judgments in the original study by Laeng and colleagues (Laeng et al., 2010), but further evidence with different emotions should be described to reach a general conclusion in this domain.

To conclude, the performance in a go/no-go emotional task was lower for older compared to younger participants, but at a deeper analysis, this difference was specific only for some comparisons. We found that independently of low or high spatial filtering, younger adults outperformed older adults so that no specific conclusion about the outcome of the cortical vs. subcortical route emerged clearly. However, based on previous evidence, we speculate that

emotional expressions contained in hybrid faces are processed implicitly (Laeng et al., 2010, 2013; Prete et al., 2015a, 2014, 2018, Prete et al., 2015c), so in the go/no-go task used here a floor effect emerged in both age groups when positive and negative hybrid stimuli had to be explicitly recognised as emotional vs. neutral. The results of the present study also confirmed that faces are processed holistically, showing that the expected face-inversion effect persists at any age (Boutet and Faubert, 2006) and that happiness is the most straightforward emotion to be recognised (Leppänen and Hietanen, 2004). No positivity bias specific to ageing emerged from the present study (Reed and Carstensen, 2012; Zebrowitz et al., 2015). Still, data confirmed a better performance in processing happiness compared to anger in both younger and older participants. We suggest that no specific effects of ageing on the activity of the dual route implicated in emotion processing are evident (Johnson, 2005; LeDoux, 1996), but a general decrement in emotion detection emerged through the go/no-go task, confirming a general perceptual and/or cognitive worsening in the elderly, without compromising global analysis or a specific emotion. Although further studies, mainly involved neuroscientific methodologies, are needed to directly show the activity of the two routes in ageing, the present results are the first evidence of a normal and expected worsening of perceptual processing of emotions with ageing, without a specific impairment in the functioning of both the cortical-conscious and the subcorticalunconscious route.

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CHAPTER 3: Pleasure before business: emotions and age effects on daily activity scheduling

Chapter 2 examined how older and younger adults process emotional stimuli across different spatial frequency and considered the role of face inversion in modulating these effects. It highlighted the extent to which aging influences the brain's ability to decode and respond to emotional cues. These insights provide a foundation for understanding how these mechanisms might shape broader cognitive and behavioral patterns.

Building on the findings of Chapter 2, this chapter shifts focus to the practical implications of aging in everyday decision-making. Activity scheduling, as a critical aspect of daily life, reflects the interplay of cognitive, emotional, and motivational processes. It involves evaluating costs and benefits alongside personal preferences for engaging in pleasant or unpleasant activities. According to Socioemotional Selectivity Theory (SST), older adults tend to prioritize emotionally meaningful goals and exhibit a stronger focus on positive stimuli due to their perception of limited future time. However, empirical investigations into temporal preferences remain limited. Moreover, the role of affective states, such as negative affect, in modulating these preferences—especially among older adults—has not been sufficiently explored. Addressing these gaps, Chapter 3 aims to provide a detailed examination of how younger and older adults prioritize and schedule emotionally charged activities, contributing to a more comprehensive understanding of the intersection between emotion regulation, decision-making, and aging.

1. Introduction

Choosing what activities to do in the future is a daily process. The scheduling process

usually involves an evaluation of the costs and benefits of the resources to be invested, in terms of energy and time. Effective scheduling, in fact, includes a priority analysis of the activities to be carried out to achieve specific objectives (Koch & Kleinmann, 2002). However, the selection of activities also depends on individual needs and subjective preferences on how to invest the time, that is, preferences on when to engage in pleasant, unpleasant, or neutral activities. Evaluations and preferences may change with aging, both for changes in cognitive functions and for variations in life perspectives and expectancies (Claessens et al., 2007). Indeed, older adults are more motivated to collect and accumulate positive experiences, preferring activities and relationships that can ensure an improvement in mood and well-being in the present time (Lang & Carstensen, 2002). Crucially, a large body of studies has shown that time perspective and time processing change with aging (Rönnlund et al., 2017).

Older adults perceive time's flow faster than younger adults, resulting in lower accuracy in time judgment tasks (Micillo et al., 2021). Furthermore, temporal source memory of older adults is significantly impaired, causing more errors in the temporal positioning of past events compared to younger adults (Ceccato et al., 2022; Noack et al., 2013). Older adults also showed compromised future thinking ability, mirroring the difficulties experienced in the temporal organization of past experiences and memories (Rendell et al., 2012).

An influential account explaining the age-related changes in time perspective is the socioemotional selectivity theory (SST). According to this theory, older adults perceive the time horizon as more reduced and constrained compared to younger adults (Carstensen, 2006). This change in time perspectives influences personal goals, and older individuals are more motivated to collect and accumulate positive experiences, investing resources mainly in activities and relationships that can ensure an improvement in mood and well-being in the present time. According to the SST, this propensity acts as an emotion regulation strategy. Moreover, extensive evidence supports the idea of a preference for positive events, objects, and memories in

aging (Carstensen, 2006; Fairfield et al., 2015; Löckenhoff & Carstensen, 2004). This attitude is known as the “positivity effect” and has been observed in memory, perception, and attention tasks (Di Domenico et al., 2015; Mammarella et al., 2017; Mather & Carstensen, 2005; Reed et al., 2014). This positivity bias appears to emerge with aging as an evolutionary compensatory effect, serving as a further emotion regulation strategy in approaching the end of one’s life. Indeed, throughout the entire lifespan preceding aging, a negativity bias appears to be prevalent. This phenomenon with opposite valence is known as the “negativity effect” and reflects children’s and younger adults’ enhanced focus on negative stimuli (Carstensen & DeLiema, 2018; Kauschke et al., 2019). Several studies have investigated the negativity effect, demonstrating how the processing of negative stimuli requires greater cognitive effort in terms of attention and perception compared to positive and neutral stimuli. As a consequence, the negative stimuli are more stably encoded in memory (Ito et al., 1998; Ito & Cacioppo, 2000). This effect can also have a significant impact on individuals’ decision-making. For the Prospect Theory, the negativity bias may be link to the phenomenon of “loss aversion” (Taylor, 1991). Specifically, when individuals face a choice involving both gains and losses, losses (negative stimuli) are more salient in the decision-making process, receiving greater importance than gains (positive stimuli) (Kahneman & Tversky, 2012). This effect seems to provide an evolutionary advantage, whereby the increased elaboration and storage of negative information contributes to greater survival and enables the avoidance or better coping the same negative experiences in the future (Norris, 2021; Rozin & Royzman, 2001; Vaish et al., 2008). In daily life, all the activities that people schedule have emotional valence, since they are spontaneously classified as more or less pleasant, unpleasant or neutral. In studies of emotions, stimuli can be emotionally classified through a categorical model and a dimensional model. The categorical model involves the specific attribution of the type of emotion elicited by the stimulus, such as happiness, anger, sadness, surprise, disgust, and fear (Ekman, 1992). The dimensional model, or circumplex model, involves evaluating the valence dimension (negative, neutral, and positive) and arousal

dimension (calm, neutral, and exciting) of a stimulus. In this study, we classified scheduling activities based on the valence dimension, ranging from negative to positive, with neutral in the midpoint (Russell, 1980). This affective connotation could influence the assignment of priorities during the scheduling process. Research indicated that younger adults often choose negative stimuli as the first and keep positive stimuli at the end of a sequence, showing a sort of “save the best for the last” tendency (Castillo, Sun, Frank-Crawford, & Borrero, 2022; Castillo, Sun, Frank-Crawford, Rooker, et al., 2022). Regarding older adults, evidence is sparse and far from conclusive (Strough et al., 2019). For instance, Löckenhoff and colleagues (Löckenhoff et al., 2012) found that in a sequence-preference task, older adults preferred to see negative pictures lastly, compared to pictures with positive and neutral valence. However, no age-related differences emerged when presented with physical and cognitive efforts sequence-preferences tasks (Löckenhoff et al., 2019, 2020). In these studies, both younger and older participants selected an improving sequencing, in which the better outcomes (i.e., easier tasks) were saved for the end.

Starting from these premises, the present study aimed to examine differences between younger and older adults in time preferences for future activities as a function of activities’ emotional valence. We created an ecological scheduling task reproducing a real-life context to avoid the potential confounding effects of motivational aspects and task complexity on older adults’ performances. Hence, the selected programmable activities represented common activities in everyday life, with positive, negative, and neutral valence, such as opening a gift and paying a fine. People were requested to plan emotional activities within a 30-day time frame, assigning one activity for each day. This experimental paradigm differed from those previously implemented as it was both hypothetical (i.e., people just thought about activities, without experiencing them) and with a longer time frame (compared to few minutes/hours used in past studies).

Based on the literature, we formulated two main hypotheses: (1) older adults would assign positive activities at the beginning of the schedule and move toward the end of the schedule the negative activities; (2) younger adults would plan negative activities at the beginning of the schedule, and positive activities toward the end of the schedule. In other words, we expected to find opposite trends in the two age groups in scheduling emotional activities, with older adults choosing mainly positive activities and younger adults selecting mostly negative activities, in the first positions of the calendar. As the participants' emotional state may influence the choices, we also measured the participants' affectivity (positive and negative). We speculated that individuals' mood would be related to the order of activities planned, but we did not hypothesize any specific direction for this effect, given the lack of previous studies.

2. Methods

2.1 Participants

The sample was composed of 52 healthy participants divided into two groups: 26 younger adults (women, $n = 12$) and 26 older adults (women, $n = 15$). The group of younger adults was aged between 19 and 33 years ($M = 25.54$, $SD = 3.39$) and had between 13 and 16 years of education ($M = 14.85$, $SD = 1.49$). The group of older adults was aged between 65 and 87 ($M = 71.96$, $SD = 7.30$) and had between 8 and 18 years of education ($M = 11.46$, $SD = 3.64$). Older adults had significantly fewer years of education than younger participants, $t(50) = 4.39$, $p < 0.001$. Furthermore, all participants completed the Beck Depression Inventory-II (Beck et al., 1996), a 21-item self-reported questionnaire assessing the severity of depressive symptomatology, to exclude any participants at risk of depression. No participant was excluded, as scores were very low (younger, $M = 6.65$, $SD = 3.60$, range 1–13; older, $M = 6.38$, $SD = 3.38$, range 1–15). Also, no age-related differences emerged, $t(50) = 0.28$, $p = 0.782$. Finally, older adults were screened with the Mini Mental State Examination (Folstein et al., 1975) to exclude participants with potential cognitive impairments. All the older participants achieved a MMSE

score of at least 24 points ($M = 27.96$, $SD = 1.04$, range 26–30).

Participants were Italian volunteers recruited through word-of-mouth and received no compensation for their participation. Before starting the experiment, participants read and signed a written informed consent. The study has been performed in accordance with the principles stated in the Declaration of Helsinki and was approved by the Institutional Review Board of Psychology of the Department of Psychological, Health and Territorial Sciences, “G. d’Annunzio” University of Chieti-Pescara.

2.2 Procedure and materials

Each participant was seated in a quiet room with equal brightness and not exposed to sources of disturbance. First, MMSE (only for older adults), PANAS, and BDI-II were administered in this fixed order. Then, the Emotional Scheduling Task was administered.

2.3 Emotional scheduling task

For the creation of the experimental stimuli, we formulated ex novo 55 plannable activities (22 positive, 17 negative, and 16 neutral). A preliminary rating study to assess the emotional valence of these 55 activities was conducted on a sample of 187 students of the “G. d’Annunzio” University of Chieti-Pescara (women, $n = 152$; age: $M = 20.37$, $SD = 3.77$; years of education: $M = 13.18$, $SD = 0.72$). We used the Self-Assessment Manikin [44], a 9-point Likert scale requesting to indicate emotional valence from 1, very negative, to 9, very positive. A score of around 5 indicates stimuli with neutral valence. Specifically, we adopted the following score ranges to classify the emotional valence of the activities: a mean score of " $M < 4$ " for the negative, a mean score of " $4 \leq M \leq 6.5$ " for the neutral, and a mean score of " $M > 6.5$ " for the positive. Based on these score ranges, we selected 30 stimuli: 10 positive ($M = 8.12$, $SD = 0.29$), 10 negative ($M = 3.38$, $SD = 0.67$) and 10 neutral activities ($M = 5.41$, $SD = 0.60$) (see the Supplementary Information online for a list of the activities selected).

The 30 selected activities were written, printed, cut, and plasticized with a size of 4.5×4.5 cm. A calendar with a 30-day period was created in the form of a grid, each cell measuring 5×5 cm, and was printed on a horizontal sheet of paper (21.00×29.70 cm) and plasticized. Finally, pieces of Velcro (1×1 cm) were glued both on each day of the calendar and behind each activity, to facilitate the placement of the stimuli on the calendar sheet.

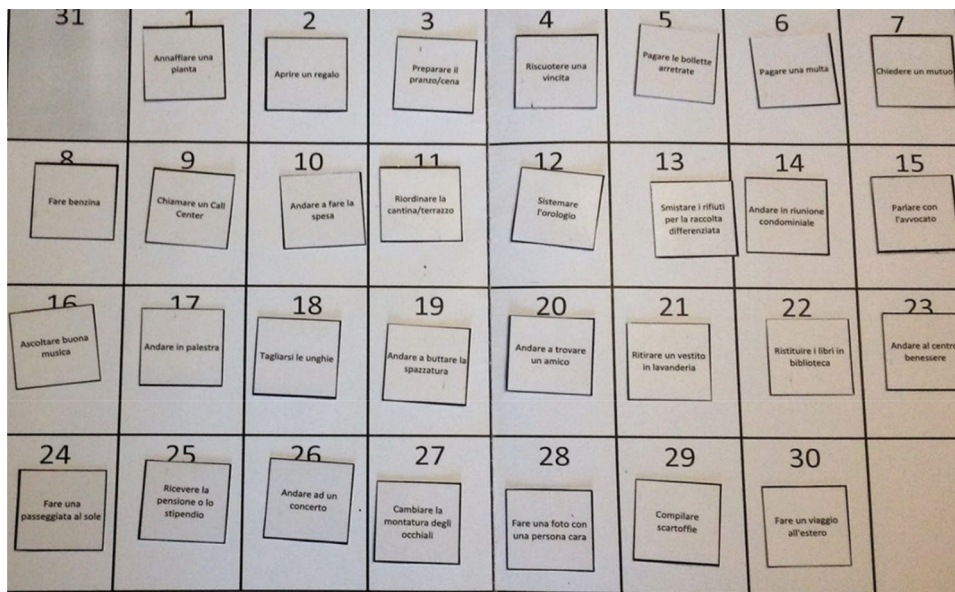


Figure 2. Emotional Scheduling Task: example of a final arrangement of the activities in the calendar.

The task requested participants to place each emotional activity on one of the 30 empty cells of the calendar. The calendar sheet was placed in front of the participant, and the instructions were given orally by the experimenter. Activities were given by the experimenter one at a time in random order. For each day on the calendar, only one activity could be assigned. The participant was allowed to change the order of the activities already entered at any time. When all activities were assigned, and the participant stated to have concluded, the final positioning was recorded and scored later (Fig. 2). Once the task was concluded, the experimenter fully explained the purpose of the study and thanked the participant.

The SI was developed to examine the preferences for the positioning of activities. Three

scores were computed, separating positive, negative, and neutral items. Each SI score was computed by averaging the positions (from day 1 to day 30) given to the activities with the same emotional valence. For example, if all the ten positive activities were planned in the first ten days of the calendar, the Positive SI score would be the sum from 1 to 10 (i.e., 55), divided by the number of activities, producing a score of 5.5. Therefore, the closer the index was to the minimum value (5.5), the more the activities with the same valence were distributed in the first days of the month. On the contrary, high SI scores indicated that activities were placed in the final part of the month (the maximum score was 25.5).

2.4 Positive affect and negative affect scales (PANAS)

We evaluated the participants' affective states by administering the PANAS scale (Watson et al., 1988). PANAS is one of the most used questionnaires to evaluate positive and negative affective states and consists of 10 positive adjectives (PA) and 10 negative adjectives (NA). Participants rated how much they felt as described by the adjective during the previous week by responding on a 5-point Likert scale from 1, "not at all", to 5 "a lot".

3. Results

A Scheduling Index (SI) was created to analyse activities' positioning preferences. Repeated measures ANOVA was performed on SI scores to assess age-related differences in scheduling as a function of activities' emotional valence. Age group (younger vs. older) was the between-subject factor, and Valence (positive, neutral, vs. negative) was the within-subject factor. The SI scores did not significantly deviate from a normal distribution, Shapiro–Wilk tests, $p_s \geq 0.109$, and the assumption of homogeneity of variance was met, as indicated by Levene's test, $p_s \geq 0.409$.

Following pairwise comparisons (Bonferroni adjusted) indicated a main effect of valence, $F(2, 100) = 40.37$, $p < 0.001$, partial $\eta^2 = 0.45$ (Fig. 1; see Table 1 for means and standard deviations). Results revealed that positive and neutral activities were planned closer in time

compared to negative activities, $ps < 0.001$. Also, the Positive SI was smaller than the Neutral SI, yet this difference was not statistically significant, $p = 0.061$.

Crucially, a significant interaction effect Age group x Valence emerged, $F(2, 100) = 11.08$, $p < 0.001$, partial $\eta^2 = 0.18$. Following Bonferroni adjusted pairwise comparisons showed that, for both younger and older adults, negative activities were planned more distant in time compared to neutral activities, $p = 0.003$ and $p < 0.001$, respectively. However, only for older adults, the Negative SI was greater than the Positive SI, $p < 0.001$, and the Neutral and Positive SI significantly differed, $p = 0.002$.

Inspecting age-related differences, we found that older and younger adults did not differ in Neutral SI, $p = 0.745$. However, older adults showed smaller Positive SI ($p < 0.001$) and greater Negative SI ($p < 0.001$) compared to younger adults. This indicates that older adults tended to plan positive activities first, and negative activities later, to a greater extent than younger adults.

Finally, we examined whether affect was related to activity scheduling. Preliminary analyses indicated that both age groups scored high on the PA scale (younger, $M = 31.88$, $SD = 3.00$; older, $M = 32.42$, $SD = 6.51$) and low on the NA scale (younger, $M = 19.15$, $SD = 5.60$; older, $M = 18.69$, $SD = 5.72$). The two age groups did not significantly differ in affect, neither in positive, $t(50) = 0.38$, $p = 0.703$, nor negative, $t(50) = 0.29$, $p = 0.770$. We conducted correlation analyses separating the two age groups.

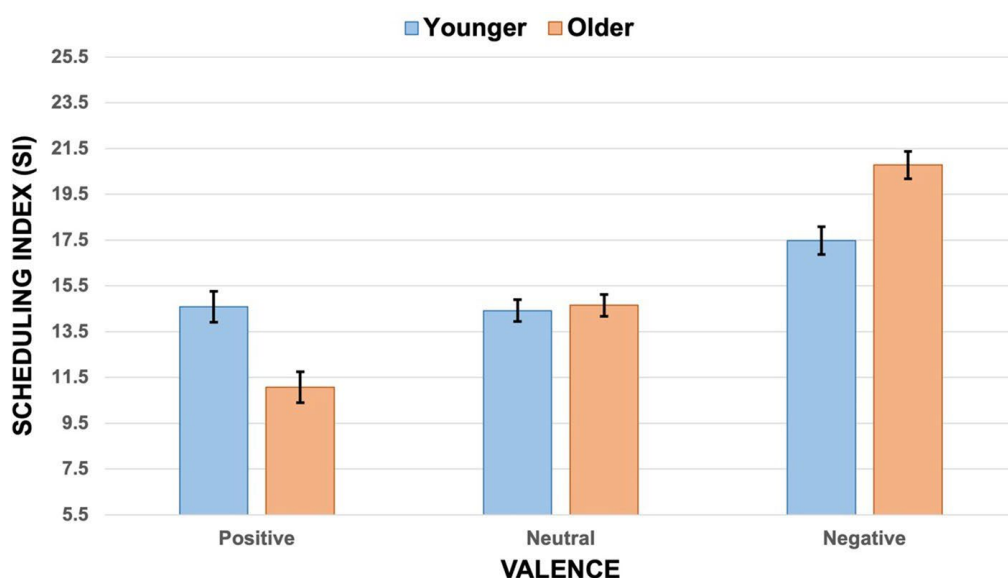


Figure 1. Analysis chart: scheduling index for activities as a function of valence and age group (vertical bars denote 95% confidence intervals).

	Younger		Older		Full sample	
	M	SD	M	SD	M	SD
Positive SI	14.59	0.67	11.07	0.67	12.83	3.84
Neutral SI	14.42	0.48	14.65	0.48	14.53	2.44
Negative SI	17.48	0.60	20.78	0.60	19.13	3.48

Table 1. Emotional Scheduling Task Results (SI = Scheduling Index): means (*M*) and standard deviations (*SD*) separated by age group.

To control for multiple comparisons, we adjusted *p* values with the Benjamini–Hochberg correction (McDonald, 2014), setting the false discovery rate to 0.05. Results indicated that affect, both positive and negative, was not related to younger adults’ emotional scheduling preferences, adjusted $ps \geq 0.238$. Interestingly, older adults with higher negative affect planned positive activities closer in time, as reflected by their lower Positive SI, adjusted $p = 0.049$ (Table 2).

	Younger		Older	
	PA	NA	PA	NA
Positive SI				
<i>r</i>	0.15	0.34	0.10	−0.54
<i>p</i>	0.451	0.093	0.640	0.004
B-H adjusted <i>p</i>	0.577	0.238	0.699	0.049
Neutral SI				
<i>r</i>	0.24	−0.27	−0.15	0.33
<i>p</i>	0.233	0.191	0.481	0.097
B-H adjusted <i>p</i>	0.399	0.382	0.577	0.238
Negative SI				
<i>r</i>	−0.35	−0.17	0.02	0.33
<i>p</i>	0.083	0.398	0.937	0.099
B-H adjusted <i>p</i>	0.238	0.577	0.937	0.238

Table 2. Correlation analyses between SI scores and affect, measured with the PANAS questionnaire. PA positive affect, NA negative affect. Pearson’s *r*, associated *p* values, and *p*

values adjusted with Benjamini– Hochberg correction are reported. Significant values are in bold.

4. Discussion

This study examined age-related differences in emotional activity scheduling. In line with the SST, results indicated that older adults planned positive activities closer in time than neutral activities, revealing the presence of a “positivity effect” (Reed et al., 2014). Extending the SST to scheduling preferences, current results suggested that the constrained time horizon motivates older people to grab positive experiences immediately, scheduling pleasant activities sooner in time.

Recently, Ceccato and colleagues (Ceccato et al., 2022) showed a similar age-related preference using a temporal positioning task of emotional stimuli previously encoded. The authors observed that older adults put positive stimuli closer in time (in the near past) and pushed away (in the far past) negative stimuli, compared to younger adults. Here we found similar evidence for the avoidance of negative stimuli, as older adults planned activities with negative emotional valence more distant in time than activities with neutral valence. This result is also consistent with the studies by Löckenhoff and colleagues (Löckenhoff et al., 2012), in which older adults tended to postpone negative pictures toward the end of a sequence in a temporal discounting task, even at the cost of viewing more negative images overall. On the other side, we hypothesized that younger adults would plan negative activities at the beginning of the schedule, and positive activities toward the end of the schedule. The literature showed that younger adults tend to prioritize negative stimuli and experiences, showing a preference for improving sequences (Carstensen & DeLiema, 2018). This negative time preference may represent an evolutionary advantage, allowing people to immediately face and resolve a problematic situation and to safely move to other activities (Baumeister et al., 2001). However, we found no evidence

of such an effect. Instead, younger adults planned negative activities more distant than neutral activities, as older adults did. We speculate that this could be due to the type and number of stimuli we used in the study. In fact, the negative activities we asked to plan had a low level of dangerousness, rather evoking fatigue and annoyance. Consequently, the evolutionary mechanism was not triggered, and younger adults postponed negative stimuli. Furthermore, the preference for improving sequences has been found when the number of outcomes was limited in size, potentially requesting less effort to select the sequence. Studies requesting to order a greater number of stimuli/outcomes showed a less consistent pattern of results (Castillo, Sun, Frank-Crawford, & Borrero, 2022; Castillo, Sun, Frank-Crawford, Rooker, et al., 2022).

Notably, in our study, older adults showed a stronger tendency to postpone negative activities compared to younger adults. It is possible that for both the age groups, negative activities, beyond unpleasantness, had an intrinsic tiring nature -they are both physically and cognitively expensive- and thus avoided. However, the negative valence of the stimuli had a greater impact on older adults compared to younger adults. Based on the Selective Engagement Theory, due to their limited cognitive resources, older adults tend to actively select where to allocate attention and energy (Hess, 2014). Hence, they may be further motivated to avoid effortful activities. Overall, our findings indicated that irrespective of age, people tend to postpone activities with a negative emotional valence, but this effect got more robust with age.

Finally, results suggested that older adults, but not younger adults, may use scheduling as an emotion regulation strategy (Charles, 2010). Correlation analysis showed that higher negative affect in this age group was associated with lower SI for positive activities. In other words, older adults with greater negative affect also showed a greater tendency to keep positive stimuli close in time. This may be an effective strategy to cope with negative emotions in daily life. Practically, older people experiencing negative emotions could decide to plan a series of positive events within a short timeframe to restore their mood. In general, past research showed that older

adults are more likely than younger adults to engage in emotion regulation activities, actively seeking to preserve positive affect (Gross et al., 1997). For example, compared to younger adults, older adults limit their interpersonal interactions to those they are familiar with and care the most about. In this way, they expose themselves to mainly predictable and positive emotional experiences (Fredrickson & Carstensen, 1990).

In conclusion, the present findings showed that younger and older adults are differently affected by emotions in scheduling daily activities. Older adults showed both a preference for positive activities and an avoidance of negative activities, in line with the SST. Younger adults only showed the tendency to postpone negative activities, but to a small extent compared to older people. Furthermore, we found preliminary evidence that older adults use scheduling future activities as an emotion regulation strategy.

This study has some limitations that should be considered in interpreting the results. First, in examining the effect of aging, we focused on an age range potentially too wide. Past studies highlighted the importance of not considering people over 65 as a homogenous “older adults” population (Ruthig et al., 2019). For this reason, future studies should replicate these analyses by considering, for example, two different samples of older adults aged 65–74 and over 75 because the positivity effect may be more salient with aging (Ceccato et al., 2022). Furthermore, based on the theoretical framework we assumed, we took for granted, but not directly assessed, age-related differences in time perspective. In future works, it may be interesting to evaluate individual differences in the time horizon of the participants, administering tests such as the Future Time Perspective (Lang & Carstensen, 1994). Finally, we classified stimuli into positive, negative, and neutral activities based on a preliminary rating conducted on younger adults. Even if we feel confident that older adults would classify each activity as younger adults did, we cannot exclude that a given activity could be perceived slightly differently by younger and older adults. Similarly, a more gender-balanced evaluation would be necessary since the rating sample

consisted of 81% females, and the activities may have a gender bias in the affective connotation. Therefore, future studies should establish a standard set of emotional activities both to avoid the potential confounding effect of age and gender on the perceived valence of the stimuli and to assess the levels of effort and arousal elicited by the activities.

Notwithstanding these caveats, the study offers intriguing insights into people scheduling preferences, starting to fill a gap in the literature on the interplay between emotions and time. Current results also have practical implications for older adults, as emotions may inadvertently affect how people plan their activities in daily life. To sum up, the common saying “business before pleasure” does not seem to hold in aging

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CHAPTER 4: Through Life's Clock: Evolution of Time Perception During Lifespan

Chapter 3 demonstrated that older adults, compared to younger adults, preferentially scheduled positive activities closer in time, consistent with the well-documented '*positivity effect*'. Conversely, both younger and older adults tended to postpone negative activities to later dates, reflecting a common tendency to defer unpleasant tasks. Interestingly, for older adults, negative affect was associated with an increased preference for scheduling positive activities sooner, suggesting an adaptive strategy to counterbalance negative emotions. These results underscore age-specific differences in how emotional content influences temporal decision-making and provide a framework for exploring broader cognitive mechanisms involved in time perception. Indeed, older adults tend to exhibit diminished performance in time perception tasks, particularly in the conditions of time reproduction and temporal bisection.

Chapter 4 investigates temporal cognition more directly, examining how individuals across the lifespan, from adolescence to late adulthood, estimate and manipulate time intervals. By focusing on tasks requiring time reproduction, bisection, and doubling, the study explores whether could emerge systematic errors observed in time perception, focusing on differences in age groups.

1. Introduction

The dimension of time plays a fundamental role in our daily lives and it is essential for predicting and managing time intervals accurately (Kononowicz et al., 2018). The importance of time dimension derives from the awareness that time durations naturally organize and characterize our lives. Since all stimuli and activities have a temporal extent, we plan our experiences, schedule our activities, and make sense of the world around us within the

fundamental framework of time (Allan, 1979; Arstila & Lloyd, 2014; Buhusi & Meck, 2005; Grondin, 2001; Wittmann, 2013). The dimension of time invades all the memories of our life experience (Rhodes, 2018), with a massive effect on episodic memory (Tulving, 2002). The cognitive ability to estimate time finds theoretical support in the Scalar Expectancy Theory (SET) proposed by Gibbon et al. (1984), according to which humans possess an internal clock system for precise time measurement. This theory explains how humans perceive and process time intervals through three interconnected stages: clock, memory, and decision. The clock stage involves an internal pacemaker that generates pulses and monitors the passage of time. Then, the memory stage stores the accumulated pulses, encoding the subjective experience of time. Lastly, the decision stage compares the subjective representation with objective time to select an appropriate response (Gibbon et al., 1984).

At the neurobiological level, Walsh (2003) proposed a model suggesting the existence of a shared neural substrate for the representation of time, space, and numbers (Walsh, 2003). This model introduces the concept of a Mental Time Line (MTL), where quantities, including small and large time intervals, are mentally organized along a hypothetical horizontal line extending from left to right. A body of evidence has supported this model at both behavioral and neural levels, utilizing various paradigms and tasks (Macnamara et al., 2018; Prete, 2020; Prete et al., 2021). Moreover, research has demonstrated that duration estimates can vary depending on specific task demands, further emphasizing the dynamic nature of temporal representation (Droit-Volet et al., 2011). Indeed, humans are not perfect "time perceivers" and often make systematic errors in estimating time, particularly when subjective biases or environmental conditions interfere (Matthews & Meck, 2016). Emotions can have a great impact on the perception of time: positive and negative affects hasten the perception of time while withdrawal-motivated affects slow the perception of time (Ceccato et al., 2022; Gable et al., 2022). This can account for the common perception of everyday life that time seems to pass more slowly during moments of boredom than during moments of enjoyment. Furthermore, the development and decline of

abilities linked to the internal clock and executive functions can also significantly influence time perception across the lifespan (Baudouin et al., 2019; Gallego, Hiroyasu & Yotsumoto, 2021; La Malva et al., 2023; Mioni et al., 2020). Recent researches using implicit testing paradigms, such as eye-tracking techniques, show that even newborns exhibit a rudimentary sense of time, as they can perceive event durations and temporal gaps between events (Addyman et al., 2014; Brannon et al., 2004, 2008; Droit-Volet, 2013; Provasi et al., 2011). As cognitive abilities, such as working memory and attentional control – particularly selective attention and inhibition – develop throughout childhood and adolescence, they contribute to improved timing performance and a more refined sense of time perception (Anderson & Reidy, 2012; Gathercole, 2002; Hallez & Droit-Volet, 2017; Suarez et al., 2020; Zélandi & Droit-Volet, 2011). These cognitive advancements influence the functioning of the internal clock system and enhance the accuracy and consistency of time-related tasks across the lifespan (Lustig & Meck, 2001, 2005). Specifically, results from studies focused on the development of time perception indicate that the capacity time processing ability remains stable from late childhood (around 9 or 10 years old) through adolescence (12-17 years old) (Szelag et al., 2002; Zélandi & Droit-Volet, 2011). Additionally, adolescents are capable of differentiating between distinct time intervals with a high degree of accuracy and reproducing target durations with notable precision, reflecting the maturation of underlying cognitive and neural mechanisms supporting temporal estimation (Siu et al., 2014; Szelag et al., 2002). Similarly to adolescents, adults in the age ranges between 19-25 and 35-55 typically demonstrate high levels of accuracy in time processing, reflecting the good functioning of cognitive and neural systems responsible for time perception in this age group (Carrasco et al., 2001; Gallego Hiroyasu & Yotsumoto, 2021; Siu et al., 2014). In late adulthood, time estimation abilities often decline, with older adults demonstrating slower and more variable performance in tasks involving rhythm monitoring, time reproduction, and discrimination (Gallego Hiroyasu & Yotsumoto, 2021). Difficulties are particularly pronounced in tasks that demand attention, such as the bisection task, which requires dividing time intervals mentally

(Lamotte & Droit-Volet, 2017). The cognitive processes underlying these errors have been linked to disruptions in the core clock system, which interacts with broader temporal information processing mechanisms, including working memory, attention, and executive control (Bisiacchi & Cona, 2016; Turgeon et al., 2016). A recent research by La Malva et al. (2023) highlighted that older adults may be particularly susceptible to variability in the encoding and retrieval of temporal information. Specifically, older adults tend to underestimate the temporal duration of previously presented negative stimuli and overestimate positive stimuli, reflecting an impact of emotional factors on time perception (La Malva et al., 2023).

Summary, it is worth noting that the accuracy pattern observed in time processing in adolescence and adulthood may not be stable respect to older adults and to different aspects of time processing, highlighting the need for further research using diverse paradigms and comparing different age groups to fully understand life-span changes. In this context, Momi et al. (2023) adopted a novel paradigm to examine time perception in adulthood in which participants were specifically instructed to actively "produce" a specific time interval, which could be identical (reproduction), half (bisection), or twice (doubling) the duration of reference intervals. Participants demonstrated accurate reproduction of time intervals, reflecting the proper functioning of the internal clock. Furthermore, it was observed that during the bisection task, they tended to overestimate time intervals, and during the doubling task, they tended to underestimate them (Momi et al., 2023). These findings suggest that when temporal information is mentally manipulated, systematic errors occur also in a sample of younger adults. According to the Mental Time Line (MTL) framework, bisection tasks cause a leftward shift, leading to underestimation, while doubling tasks cause a rightward shift, resulting in overestimation. Starting from these results, the present study adopted this innovative paradigm including other age groups (from adolescence to old age) to investigate possible age-related differences in this highlighted pattern of systematic errors.

1.1 The current study

We specifically compare the time estimation performance of different age groups: Adolescents (AD; ages 10 to 17), Younger Adults (YA; ages 18 to 35), Adults (A; ages 35 to 64), and Older Adults (OA; ages 65 to 85).

The primary aim of this study is to investigate whether in these different age groups could emerge the same pattern of systematic errors observed in YA in the study of Momi and colleagues (2023). Authors explained this pattern of results as a kind of aftereffect, due to the short-term retention (adaptation) to the subjective representation of shorter (bisection) vs longer (doubling) intervals, which makes these two tasks more difficult than reproduction. If these systematic errors are observed across the lifespan, it could suggest that the cognitive processes underlying temporal judgments—such as attentional control, working memory, and executive functioning—may influence temporal processing, regardless of age. Furthermore, these errors may reflect the inherent mental manipulations involved in processing time intervals, which are subject to distortion through the internal clock mechanism as proposed by Momi et al. (2023). Specifically, these distortions could reflect systematic biases in the cognitive representation and manipulation of temporal intervals. In particular, based on previous literature, we predict that adolescents will show no significant differences in temporal tasks compared to other age groups, consistent with findings by Li et al. (2022) and supporting the theory that the internal clock and time processing abilities are formed and stabilize during late childhood (around 9 to 10 years of age) (Li et al., 2022; Siu et al., 2014; Szélag et al., 2002; Zélandi & Droit-Volet, 2011). Notably, no previous studies have investigated time doubling in adolescents, leaving this aspect exploratory. For younger and middle-aged adults, we expect the results to replicate the patterns reported by Momi et al. (2023), with high accuracy in reproduction tasks, overestimation in bisection tasks, and underestimation in doubling tasks, reflecting the same cognitive processing biases in time estimation. For older adults, we anticipate slight worsening differences in

performance (Baudouin et al., 2019; Gallego Hiroyasu & Yotsumoto, 2021), particularly in the bisection and doubling task, which may reflect age-related changes in attentional or working memory processes (Lamotte & Droit-Volet, 2017). These differences may manifest in a reduced accuracy in time estimation compared to younger adults.

2. Materials and methods

2.1 Participants

A total sample of 603 participants (377 females), with a mean age of 37.44 years ($SD = 22.64$) were included for the analysis of the present study. YA were undergraduate students recruited at the University of Chieti while participants of the other age groups (AD; A; OA) were recruited through social media and word-of-mouth from the local community. All participants took part in the study as volunteers. They signed an informed consent prior to take part in the study, which was approved by the local ethical committee. All participants self-reported normal or corrected to normal vision and absence of auditory impairments, neurological and/or psychiatric conditions. Participants with a mean score three standard deviations lower or higher than the mean in the specific subgroup ($n=17$) were excluded from the analysis (4 AD; 2 YA; 4 A; 7 OA). Furthermore, OA's cognitive functioning was evaluated by administering the Montreal Cognitive Assessment (MoCA) (Nasreddine et al., 2005). To control for the absence of cognitive impairments in the OA sample we used a cutoff for the MoCA score equal to 18 (Bosco et al., 2017), and therefore, five OA with a MoCA score < 17 were excluded for the present study. Statistical analyses were thus carried out on a final sample of 603 participants (see Table 1 for details of the final subgroups).

	AD (10-17 y)	YA (18-35 y)	A (35-64 y)	OA (65-85 y)
N	152	153	177	121
Age ($M \pm SD$)	13.79 ± 1.29	20.37 ± 3.00	49.12 ± 7.65	71.89 ± 8.46
Gender (male/female)	55/97	53/100	71/106	47/74
MoCA ($M \pm SD$)	-	-	-	22.77 ± 3.25

Table 1. Demographic information of the four subsamples included in statistical analyses: mean and standard deviation ($M \pm DS$) of the age; gender divided in male and female participants; $M \pm DS$ obtained at the Montreal Cognitive Assessment (MoCA) for the group OA.

2.2 Experimental procedure

The entire procedure was the same adopted in the previous study by Momi and colleagues (2022) that was conducted in the same laboratory at the University of Chieti. Each trial began with a fixation cross displayed at the center of the screen for 1500 ms, followed by a gray circle (the reference stimulus) with a duration that ranged from 1500 to 5000 ms, increasing in 500 ms intervals. Each of the eight possible durations was presented 15 times in random order. Subsequently, a screen indicating the experimental condition (Reproduction, Doubling, or Bisection) was displayed for 2000 ms. Immediately afterward, a gray square appeared (test stimulus), and participants were asked to press the spacebar to indicate the duration of the square, depending on the block condition (see Fig. 1). The task included three distinct block conditions in a within-subjects design, meaning all participants completed each of the three blocks: Bisection, Reproduction, and Doubling.

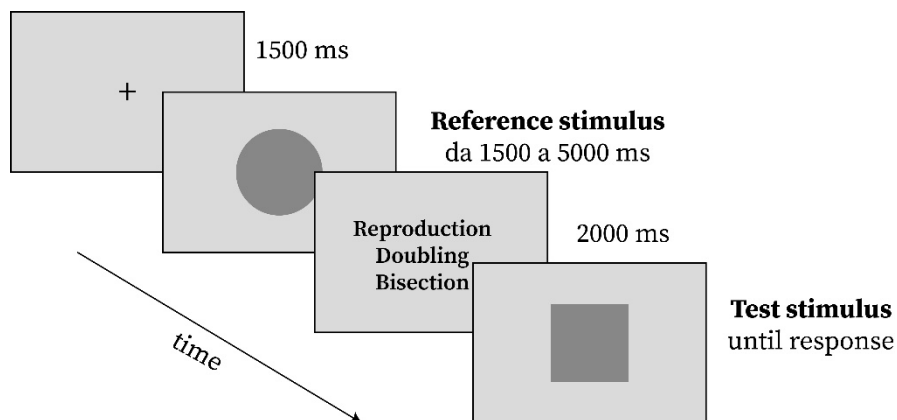


Figure 1. Experimental procedure. Each trial began with a fixation cross displayed for 1500 ms, followed by a gray circle shown for one of eight durations (1500–5000 ms, in 500 ms steps). Participants were then informed of the experimental condition (Reproduction, Doubling, or Bisection) via a 2000 ms prompt before estimating the duration of a gray square by pressing

the spacebar.

In the Bisection block, participants pressed the spacebar when the second stimulus lasted half the duration of the reference; in the Reproduction block, they responded when the duration matched the reference; and in the Doubling block, they indicated when the second stimulus lasted twice as long. A total of 120 trials were administered, with 40 trials per block. The order of the blocks, reference duration, and type of stimulus (square or circle as reference) were randomized for each participant. Participants were instructed not to mentally count during the task to ensure that their temporal judgments were based solely on their internal clock system rather than relying on external counting strategies. Participants who committed more than 10% errors were excluded from the analysis. Errors were defined as responses with reaction times below 100 ms (anticipatory responses) or exceeding 30 seconds (delayed responses). As a result, a total of 10 participants were excluded from the analysis: 3 AD, 2 YA, 2 A, and 3 OA. This criterion was applied to ensure the reliability of the data and to exclude outliers whose performance deviated significantly from expected task behavior. The experimental task was conducted using E-prime 3.0 software (Psychology Software Tools Inc.) on a 15-screen Windows laptop.

2.3 Statistical analyses

All analyses were performed using Statistica software v. 12 (StatSoft, 2013) and when needed post-hoc comparisons were performed using Tukey HSD tests (significant threshold: $p < 0.05$). The dependent variable was the time estimation error, defined as the difference between the participant's perceived duration and the actual duration of the reference stimulus. This difference was normalized using a T-corrected score (McConchie & Rutschmann, 1970; Treisman, 1963) with the following formula:

$$T - \text{corrected} = \frac{T \text{ estimated} - T \text{ standard}}{T \text{ standard}}$$

where T estimated represents the average estimation provided by the participant for a given reference stimulus duration (T standard). After normalization, negative values indicate that the test stimulus was perceived as shorter than its actual duration (underestimation), while positive values indicate it was perceived as longer (overestimation). Thus, values closer to 0 represent a more accurate time estimation.

3. Results

In the first step of the analysis, three single-sample t -tests were carried out, comparing the T_c value for each task condition within each age group with the correct performance corresponding to $T_c = 0$. Exactly in line with the previous evidence (Momi et al., 2023), results confirmed that T_c did not differ from 0 in the Reproduction condition (*all ps* > .117). T_c was significantly higher than 0 in the Bisection condition (*all ps* < .001), reflecting an overestimation of stimuli duration. T_c was significantly lower than 0 in the Doubling condition (*all ps* < .001), reflecting an underestimation of stimuli duration (See Table 2).

	Bisection	Reproduction	Doubling
Adolescents (AD)	$t(151) = 9.46, p < .001$	$t(151) = -11.45, p < .001$	$t(151) = 1.37, p = .174$
Younger Adults (YA)	$t(152) = 8.14, p < .001$	$t(152) = -12.20, p < .001$	$t(152) = 1.58, p = .117$
Adults (A)	$t(176) = 8.61, p < .001$	$t(176) = -13.67, p < .001$	$t(176) = -0.71, p = .480$
Older Adults (OA)	$t(120) = 7.15, p < .001$	$t(120) = -6.17, p < .001$	$t(120) = 0.67, p = .502$

Table 2. Results of single-sample t -tests comparing the T_c values for each condition (Bisection, Reproduction, and Doubling) within each age group (AD, YA, A, and OA) against the correct performance ($T_c = 0$).

Finally, to fully investigate the possible effect of each factor and their interactions, a repeated measure Analysis of Variance (ANOVA) on T_c means was carried out using Age Group

(AD, YA, A, OA) as between-subject factor and Condition (Bisection, Reproduction, Doubling) as within-subject factor.

The main effect of Age Group was significant ($F(3, 599) = 3.91, p = .009, \eta p^2 = 0.02$). Post-hoc analysis revealed that OA exhibited significantly higher mean estimates of stimulus duration than A, suggesting a tendency to overestimate temporal intervals ($p = .003$).

The main effect of Condition was significant ($F(2, 1198) = 596.65, p < .001, \eta p^2 = 0.50$). Post-hoc comparison confirmed that Tc was significantly higher in Bisection compared to both Reproduction and Doubling, reflecting a pattern of overestimation (*all ps* < .001). Further, Tc was significantly lower in Doubling (indicating underestimation) when compared to Reproduction and Bisection (*all ps* < .001).

In the end, the interaction between Age Group and Condition was significant ($F(6, 1198) = 14.23, p < .001, \eta p^2 = 0.07$). Post-hoc analyses revealed that OA exhibited a greater tendency to overestimate in the Bisection condition compared to the other three age groups (*all ps* < .001). In contrast, no significant age group differences were observed in the Reproduction and Doubling conditions, reflecting similar temporal perception across all age groups (see Fig. 2).

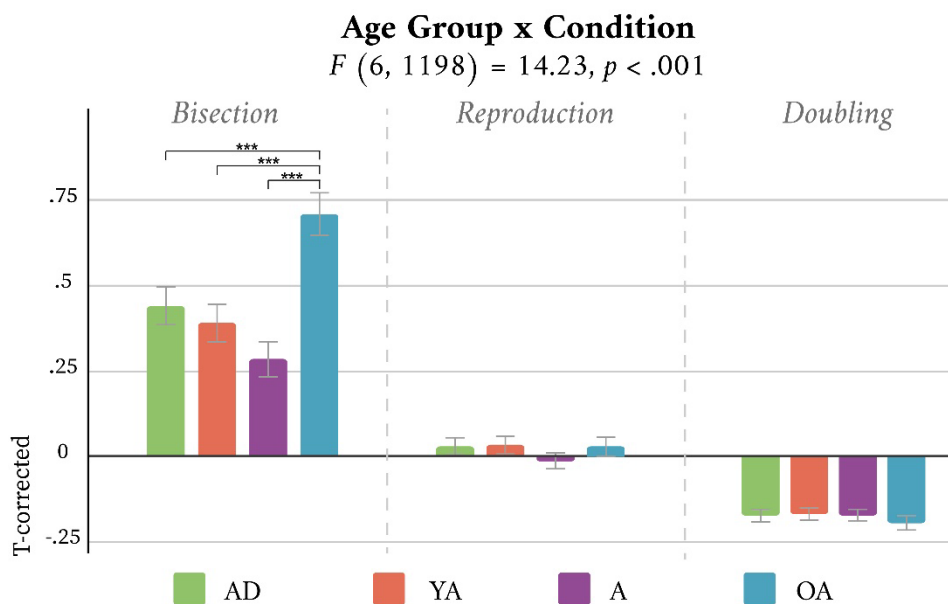


Fig. 2. Interaction among Age Group and Condition: Tc scores in Age Group divided for each Condition: Bisection, Reproduction, Doubling; bars represent standard errors, and asterisks show significant comparisons (***) ($p < .001$)

4. Discussion

The perception and representation of time are complex and sophisticated aspects of human cognition, influenced by contextual and individual factors, including emotions and age. In this study, we investigated the potential influence of the internal clock system on the cognitive ability to estimate and manipulate time across different age groups. To this end, we administered the paradigm adopted by Momi et al. (2023) in which all groups of participants (Adolescents, Young Adults, Adults, and Older Adults), were asked to estimate the same (Reproduction), half (Bisection) or twice (Doubling) duration of the reference stimulus presented.

The results reveal a consistent response pattern across all age groups, replicating the findings of Momi et al. (2023). Specifically, participants across all age groups accurately reproduced time intervals when tasked with replicating the same duration as a target stimulus. This pattern supports the theoretical framework proposed by Gibbon et al. (1984), which posits that the internal clock operates efficiently when time intervals need to be reproduced. However, performances are prone to systematic errors when mental manipulation of time intervals is involved. Indeed, when participants were required to mentally manipulate the interval duration, systematic errors emerged: they overestimated time intervals during bisection tasks and underestimated them during doubling tasks. These systematic errors can be attributed to an aftereffect phenomenon associated with the Mental Time Line (MTL) (Walsh, 2003). During bisection tasks, participants exhibited a leftward shift, leading to overestimation, whereas doubling tasks elicited a rightward shift, resulting in underestimation. Importantly, these shifts reflect the cognitive biases in the mental representation of time, wherein shorter intervals are

overestimated during bisection and longer intervals are underestimated during doubling. This tendency towards convergence aligns with perceptual aftereffects observed in other sensory modalities, where exposure to certain stimulus magnitudes biases subsequent judgments toward a central interval (Li et al., 2017; Momi et al., 2023; Palumbo et al., 2015). Crucially, this study provides new insight by demonstrating that this pattern of systematic errors occurs consistently across all age groups, highlighting that the same cognitive biases in temporal processing are present throughout the lifespan.

Regarding the performance of different age groups, a significant main effect emerged, driven by differences in temporal judgment tasks between middle adulthood and late adulthood. This finding is consistent with prior literature, which highlights that older adults tend to perform worse than middle-aged adults on tasks requiring temporal estimation. This age-related decline may be explained by the deterioration of cognitive and attentional processes underlying the internal clock system. Previous studies, indeed, have shown that age-related changes in executive functioning, working memory, and attentional control—key components of the temporal processing system—may contribute to these differences (Bisiacchi & Cona, 2016; Gallego Hiroyasu & Yotsumoto, 2021; Turgeon et al., 2016).

More specifically, results show that participants in late adulthood overestimated time intervals significantly more than other age groups in the bisection condition. This specific difficulty in the bisection condition, as opposed to other conditions, may be due to the heightened reliance on working memory and attentional control required for bisecting time intervals. The bisection task requires participants to retain a mental representation of both endpoints of the interval and actively compare them to estimate the midpoint, all within a relatively short time frame (Momi et al., 2023). In contrast, the other tasks, such as doubling, provide more time for participants to process and manipulate the temporal information. Given these demands, the bisection task may be more vulnerable to distortions in the internal clock mechanism in older

adults, as it relies on the efficient use of attentional resources and working memory. As cognitive load increases, particularly in tasks that require rapid mental manipulation, there is a corresponding reduction in performance (Block et al., 2010). Consequently, older adults may struggle more with the bisection task within the required time limits, leading to a significant overestimation of time intervals compared to younger participants. We can also speculate that healthy older adults, who are often aware of their cognitive deficits (Buckley et al., 2010; Halamish et al., 2011), might approach temporal tasks with heightened self-monitoring. Lamotte et al. (2012) observed a significant correlation between participants' awareness of time distortion and their temporal performance. Specifically, they found that the more aware participants were of potential distortions in their perception of time, the more accurate and precise their temporal judgments became (Lamotte et al., 2012). The authors suggested that this awareness leads participants to implement strategies that help mitigate their cognitive limitations. However, in the context of the temporal bisection condition, reducing the available time to complete the task, thereby increasing cognitive demands, could have the opposite effect. With more cognitive resources required to complete the task within a shorter timeframe, response times might increase as participants experience greater cognitive load, potentially leading to a slowing down of performance.

Finally, we did not observe any significant differences in the performance of adolescents across the three temporal tasks compared to younger and middle adults. Specifically, in the reproduction condition, adolescents demonstrated a high degree of accuracy in their time estimations, further supporting the theory that the internal clock system, responsible for temporal processing, begins and fully develops during childhood (Li et al., 2022; Siu et al., 2014; Szelag et al., 2002; Zélandi & Droit-Volet, 2011). Additionally, the performance of adolescents reflected the same pattern of overestimation and underestimation respectively in bisection and doubling conditions observed in adults, reflecting the same systematic errors possibly influenced by the MTL (Momi et al., 2023).

When interpreting these results, it is important to acknowledge several limitations. First, although we assessed general cognition using the Montreal Cognitive Assessment (MoCA), we did not include specific measures of attentional ability—particularly divided attention—or working memory. These cognitive functions are critical in tasks requiring temporal estimation, as they directly influence the processing and manipulation of time intervals, particularly in tasks like bisection and doubling, which demand sustained focus and active mental manipulation of temporal information. Additionally, the task employed in this study relied exclusively on visual stimuli. Prior research has demonstrated that older adults tend to perform better on temporal tasks involving auditory stimuli compared to visual ones (McAuley et al., 2010; Staub et al., 2013). This suggests a modality-specific advantage that could influence performance. Future research should consider implementing similar behavioral tasks using auditory stimuli, such as tones or sounds, instead of static visual images presented on a screen. Such an approach could reveal whether performance differences emerge based on the sensory modality, providing insights into whether auditory stimuli might mitigate the systematic errors observed in tasks like bisection and doubling. Another avenue for further exploration would involve extending this experiment to include younger participants, particularly children, divided into narrower age brackets. This would allow researchers to investigate whether the systematic errors observed in bisection and doubling tasks diminish with the development of cognitive abilities and the internal clock system, or whether these errors manifest differently across developmental stages. Understanding these patterns could provide valuable information about the role of cognitive maturation in shaping temporal processing abilities.

Despite these limitations, our study offers significant insights into temporal perception and estimation abilities across the lifespan. By examining a broad range of age groups, we have shed light on how temporal judgments are shaped by cognitive and neural processes over time. These findings contribute to a deeper understanding of the mechanisms underlying temporal cognition, paving the way for future research to refine and expand upon these results through

more comprehensive experimental designs and diverse methodologies.

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CHAPTER 5: Gamma oscillation modulation for cognitive impairment: A systematic review

The previous chapters have focused on understanding the cognitive and behavioral characteristics of healthy aging, examining the mechanisms underlying temporal perception, emotional processing, decision-making, and activity scheduling in older adults. These studies have emphasized how healthy aging is associated with specific cognitive adaptations and compensatory strategies that enable older adults to maintain functionality and well-being despite structural and functional brain changes. However, aging does not uniformly preserve cognitive functions, and for some individuals, the effects of aging manifest as significant impairments in daily life due to pathological changes. It is therefore essential to extend the exploration of aging beyond healthy populations to understand how cognitive decline and neurodegenerative conditions disrupt the mechanisms that support everyday cognitive and emotional processes.

Chapter 5 shifts focus from healthy aging to examine the critical issue of cognitive impairment in older adults, specifically in the context of Alzheimer's Disease (AD) and Mild Cognitive Impairment (MCI). These conditions represent significant challenges, as they lead to progressive deterioration in memory, executive functions, and other cognitive domains that are critical for independence and quality of life. Emerging evidence suggests that the modulation of gamma oscillations—a key neural rhythm implicated in attention, memory, and information processing—may offer a novel avenue for intervention. The objective of this chapter is to critically review the efficacy of gamma oscillation modulation techniques for cognitive enhancement in individuals with AD and MCI.

Introduction

1. Background

Alzheimer's disease (AD) is a neurodegenerative disorder marked by severe dementia, involving a progressive decline in memory and other cognitive functions (Bateman et al., 2012; Budson et al., 2016). It is the most common cause of dementia, accounting for 60% to 80% of cases globally (Alzheimer's Association, 2022; Holtzman et al., 2011). In 2022, the Alzheimer's Association estimated over 44 million people were living with AD, making it one of the top ten causes of death worldwide, with more than 1.5 million deaths in 2019 (Figure 1A). The economic impact is substantial: in the US alone, health care costs for individuals with AD or other dementias are about 321 billion dollars and are expected to rise (Alzheimer's Association, 2022).

AD progresses from a preclinical stage with no cognitive symptoms, which can extend up to 20 or 30 years before noticeable symptoms appear (Alzheimer's Association, 2022; Bateman et al., 2012). The prodromal phase, known as Mild Cognitive Impairment (MCI) due to AD, is characterized by mild cognitive decline with preserved daily function (Albert et al., 2013; Rostamzadeh et al., 2022). Approximately 15% of MCIs develop AD within 2 years, progressing to dementia that interferes with daily activities (Petersen et al., 2018). Key symptoms include memory loss, visuospatial difficulties, and executive dysfunctions. Memory, especially episodic and associative memory, is often the first affected cognitive domain. Emotional factors influence memory processes, including temporal source memory, in aging individuals (Ceccato et al., 2022). Executive dysfunctions, like difficulties with inhibition and cognitive regulation, are common and significantly impact psychological well-being (Fusi et al., 2022). These impairments highlight the complexity of cognitive deficits in AD and the need for comprehensive approaches to understanding and treating these conditions. As AD progresses, behavioral issues such as irritability, anxiety, and aggression can occur. In severe stages, patients require assistance with daily living activities and often need long-term care (Budson et al., 2016).

The clinical symptoms of AD result from brain degeneration and neuronal loss, typically presenting with cortical atrophy starting from the medial temporal lobe (Figure 1B) (Kandel et al., 2013). Microscopically, AD is characterized by extracellular amyloid- β plaques and neurofibrillary tangles (NFTs) (Lochocki et al., 2020; Wengenack et al., 2000). Amyloid- β plaques consist of aggregated amyloid- β (A β) peptides, derived from the Amyloid Precursor Protein (APP). APP is cleaved by three enzymes: α -, β -, and γ -secretase. The non-amyloidogenic process, involving α - and γ -secretase, produces extracellular P3 protein and the amyloid intracellular domain (AICD) (Müller et al., 2008). The amyloidogenic process, involving β -secretase (BACE-1) and γ -secretase, releases A β peptides into the extracellular space (Figure 1C). Soluble A β proteins are highly hydrophobic and aggregate into various forms, causing neuroinflammation. This process is central to the "amyloid hypothesis," which suggests that A β accumulation triggers a cascade of pathological events leading to neurodegeneration and AD (Oumata et al., 2022; Pomara & Sidtis, 2010; Querfurth & LaFerla, 2010). The second hallmark of AD is NFTs, intraneural cytoplasmic structures made up of paired helical filaments and straight filaments. These filaments primarily consist of hyperphosphorylated tau protein (p-tau) (Figure 1C). P-tau is crucial for intracellular transport by stabilizing microtubules, particularly in CNS axons. In AD, hyperphosphorylated p-tau disrupts axonal transport, synaptic stability, and trophic support, contributing to neuronal deterioration (Kandel et al., 2013; Trojanowski & Lee, 2002). AD diagnosis can be definitively confirmed only postmortem by detecting both amyloid- β plaques and p-tau deposits in the brain. Currently, Cerebrospinal Fluid (CSF) analysis and Amyloid Positron Emission Tomography (Amyloid-PET) are the main in vivo methods for assessing AD (Lochocki et al., 2020). These methods improve the certainty that the clinical dementia syndrome is due to AD but are not widely used due to their cost and invasiveness. Consequently, AD diagnoses often refer to probable or possible AD (McKhann et al., 2011).

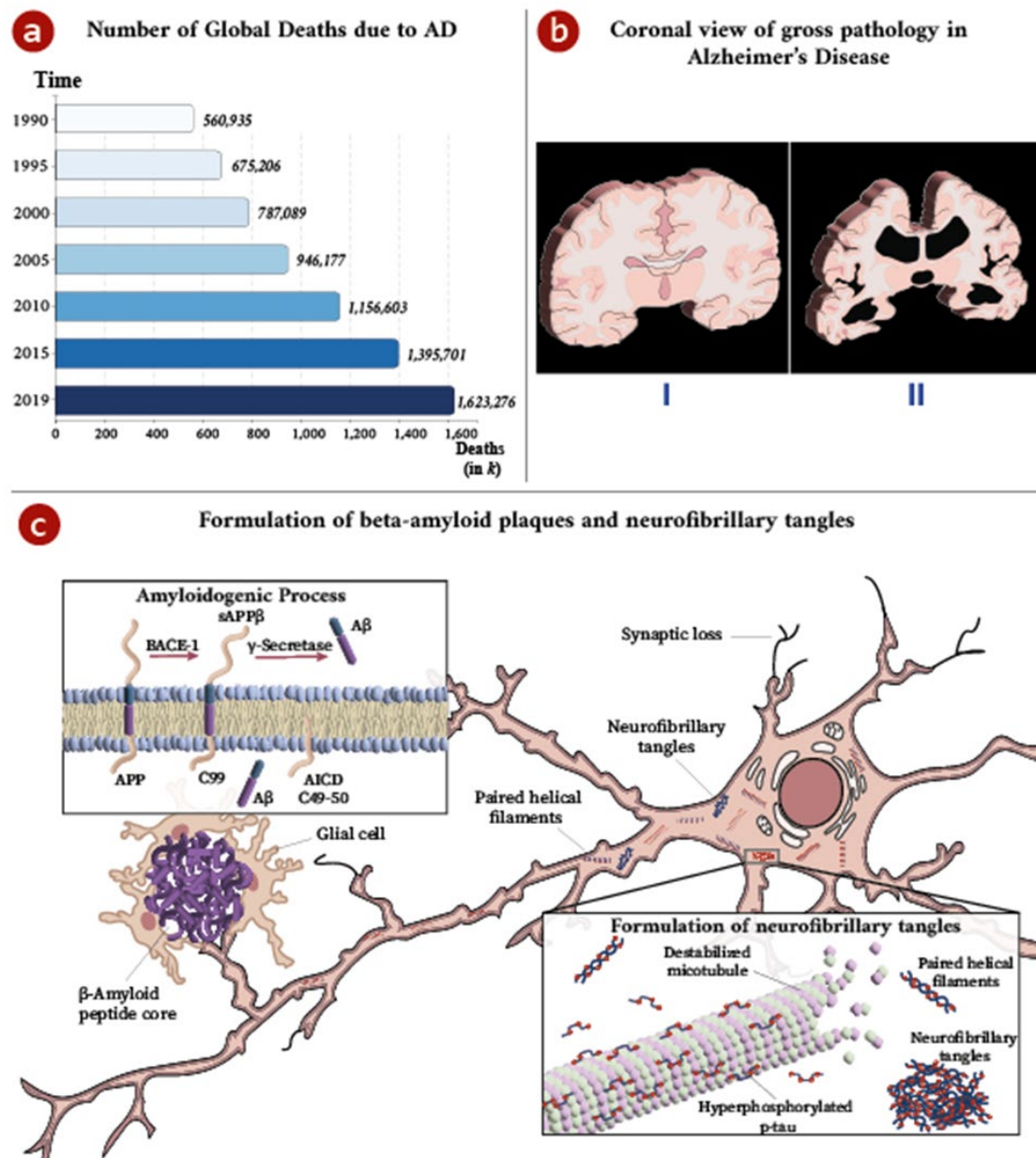


Fig. 1. Artworks created using Adobe Illustrator v 28.5. Fig. 1a shows the trend of AD-related deaths worldwide from 1990 to 2019. Source: <https://ghdx.healthdata.org/>. Fig. 1b exhibits the coronal view of a healthy brain (I) compared with a brain with AD (II). Can be seen the atrophy of the whole brain, with narrowing gyri, enlarged sulci, and thinning of the hippocampus. The figure in Fig. 1c shows a neuron containing both the hallmarks of AD: neurofibrillary tangles (NFTs) are in cell body and axon and A β plaque surrounds a dendrite, which displays a swollen shape. In the box above can be seen the amyloidogenic process leading

to the formulation of the peptide A β . The Amyloid Precursor Protein (APP) is cleaved by β -secretase beta-site amyloid precursor protein-cleaving enzyme 1 (BACE-1) releasing a sAPP β . The retained C99 is also a γ -secretase substrate, generating A β and AICD. The lower box shows the formulation of neurofibrillary tangles. Hyperphosphorylated isoform of the microtubule-associated form proteins tau (p-tau) destabilize microtubules which begin to disassemble. Then p-taus form paired helical filaments, which become sequestered in neurofibrillary tangles

1.1 Current AD treatments and new therapeutic approaches

Current treatments approved by the Food and Drug Administration (FDA) are aimed to temporarily improve AD symptoms, having no effects on the underlying brain abnormalities that cause the disease or its progression (Alzheimer's Association, 2022). In June 2021, FDA authorized, under the accelerated approval pathway, a new treatment, aducanumab, able to reduce A β plaques in the brain (Cavazzoni, 2021; Food & Drug Administration, 2021). However, it has been highlighted that aducanumab is not a risk-free treatment since it is linked to an increased incidence of amyloid-related imaging abnormalities (ARIA) which is a serious condition that can represent a sign of brain enlargement (Sperling et al., 2011). Therefore, according to Alzheimer's Association (2002), ARIA should be promptly recognized and further controlled in patients receiving aducanumab by close monitoring. Considering these unsatisfactory results and the rapid increase of the enormous financial, personal and social costs of AD, it is necessary to promptly obtain a deeper understanding of the mechanisms underlying both healthy and pathological brain aging to develop new therapeutic approaches (Bishop et al., 2010). Currently, research is exploring new possible explanations for AD etiopathogenesis, such as infection, cerebral vasoconstriction, and prion transmission (Jeong et al., 2018; Seminara et al., 2018; Tian et al., 2019). A recent innovative approach is aimed to examine changes in resting-state brain oscillations to treat AD pathology. Brain oscillations coordinate distributed cortical networks' communication at the macroscale and are implied in the modification of the

timing of neuronal spiking at the microscale (Zhang et al., 2018). In AD patients, a typical brain oscillations pattern consists of a reduction of gamma frequencies and a general enhancement of slow rhythms (i.e., delta and theta frequencies). The effect of this pattern can be crucial considering that gamma oscillatory activity (approximately 25-85 Hz) is associated with several cognitive processes, such as attention, perception, object recognition, memory processes, face recognition, and emotional paradigms (Guan et al., 2022; Jafari et al., 2020). Based on these considerations, a novel therapy aims to modulate AD gamma frequencies using Non-Invasive Brain Stimulation (NIBS). NIBS involves applying electrical or magnetic fields to the scalp to modulate brain activity. The most commonly used techniques in this field include transcranial Alternating Current Stimulation (tACS), transcranial Direct Current Stimulation (tDCS), and Transcranial Magnetic Stimulation (TMS). NIBS could improve physiological and pathological aging-related cognitive impairments through modulation of cognition, emotion, and behavior in neural plasticity (Boggio et al., 2011; Dayan et al., 2013; Vallence & Goldsworthy, 2014). From previous literature, it is now well-established that NIBS techniques (particularly tACS and TMS) can entrain brain oscillations, promoting potential improvements in cognitive functions in healthy subjects (Hopfinger et al., 2017; Hoy et al., 2015; Santarnecchi et al., 2019; Thut et al., 2011). However, recent studies using a combination of NIBS and electroencephalogram (EEG) have demonstrated the effectiveness of NIBS even in patients with MCI and AD, confirming their potential therapeutic role in cognitive decline (Kim et al., 2021; Liu et al., 2022; Naro et al., 2016; Xing et al., 2020). Additionally, virtual reality (VR) combined with cognitive rehabilitation has shown promising results in enhancing cognitive functions in older adults with MCI, highlighting the potential for integrating advanced technologies in cognitive therapies (Tortora et al., 2024).

A further innovative technique used to modulate gamma frequencies involves Gamma Sensory Stimulation (GSS). GSS is a novel non-pharmacological therapeutic approach to AD which involves manipulating gamma activity in the brain through external brain stimulation, in

particular using sensory input, such as 40 Hz light flicker or 40 Hz sound waves (McDermott et al., 2018). Several studies have demonstrated the feasibility of using GSS as a non-invasive therapeutic approach. For example, Chan et al. (2022) conducted a feasibility study where AD patients underwent daily sessions of 40 Hz light and sound stimulation for three months. The results indicated that GSS was well-tolerated, with minimal adverse effects reported. The study also showed significant improvements in associative memory tasks in the experimental group compared to the control group, highlighting the potential cognitive benefits of GSS. EEG monitoring during GSS sessions has provided valuable insights into how sensory stimulation can entrain brain oscillations. For instance, Lin et al. (2021) found that exposure to 40 Hz blue light resulted in changes in hippocampal activation and functional connectivity, as observed through EEG recordings. These changes were associated with improved performance in recognition memory tasks, suggesting that GSS can effectively modulate gamma activity in the brain. Moreover, Manippa et al. (2024) demonstrated that 60 Hz auditory stimulation reduced intrusion errors in immediate recall tasks among healthy adults, further supporting the role of GSS in enhancing cognitive processes through the entrainment of brain oscillations. EEG recordings in this study revealed significant correlations between improved cognitive performance and specific patterns of gamma activity, emphasizing the importance of real-time EEG monitoring to optimize GSS protocols. The integration of GSS with EEG monitoring holds great promise for developing effective non-invasive treatments for cognitive impairments in AD and MCI patients. The ability of GSS to entrain gamma oscillations and improve cognitive functions, coupled with its feasibility and minimal adverse effects, makes it a viable option for long-term therapeutic applications. Both NIBS and GSS are promising disease-modifying therapeutic intervention, and they could make a breakthrough on the AD treatments' research. The present systematic review aims to summarize and examine if gamma entrainment has an effective therapeutic role in the treatment of AD.

2. Methods

The current systematic review was carried out based on the guidelines and principles outlined by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement 2020 and checklist (Page et al., 2021).

2.1 Search Strategy

Studies were identified by computer-based research performed in January 2024. We searched in three literature databases: PubMed, Web of Science, and Scopus, refining search outcomes from 2015 until now. The decision to include articles from 2015 onward is motivated by the desire to capture the latest developments and advancements in research following the pivotal findings proposed by Iaccarino et al. (2016). The intention was to minimize the risk of overlooking any valuable studies that could contribute to a comprehensive understanding of the topic under investigation.

The research utilized a search string containing the following keywords: ((gamma) OR (gamma 40 hz) OR ("Gamma entrainment") OR ("Gamma activity") OR ("Gamma oscillation*")) AND ((stimulation) OR (light flicker*) ("Rhythmic sensory stimulation") OR ("frequency stimulation") OR (tacs) OR ("transcranial Alternating Current Stimulation") OR ("Transcranial Direct Current Stimulation") OR (tdcs) OR ("non-invasive brain stimulation") OR (rtms) OR ("Transcranial magnetic stimulation") OR (rtms) OR ("repetitive transcranial magnetic stimulation") OR ("repetitive neuromodulation")) AND ((alzheimer) OR ("Mild Cognitive Impairment") OR (mci) OR (dementia)) AND NOT ((mouse) OR (mice) OR (animal*) OR (rat*) OR ("in vitro")) AND NOT ((mice) OR (rat*) OR (Animal*) OR (mouse) OR ("In vitro")). Finally, we refined our search to include only articles written in English, specifying original peer-reviewed research articles as the chosen publication type.

2.2 Selection criteria and quality assessment

We included all experimental studies that employed an electrical, magnetic, or sensory gamma wave stimulation technique on populations of elderly individuals with AD, MCI, healthy elderly individuals, or young individuals. We included studies that utilized MCI samples, without specifying whether they were related to AD because of its relevance for a comprehensive examination of cognitive interventions. The decision was motivated by the recognition that MCI represents a transitional state between normal aging and more severe cognitive decline (Jessen et al., 2014), and studying interventions across this spectrum can provide valuable insights into their potential efficacy at different stages. Studies that selected samples affected by different types of dementia other than AD were not included. Studies employing a combined sample of both MCI and AD in the same experimental group were excluded due to methodological considerations. The decision to exclude such studies was driven by the aim to maintain homogeneity within the study population, ensuring a clearer and more targeted examination of the effects of the interventions, and avoiding potential confounding factors associated with major and mild neurocognitive disorders. Studies that did not have global cognition scores or individual cognitive functions scores as outcomes were also excluded. Finally, studies that did not have a control/comparison group were excluded from this review. We also included studies done in healthy older and younger adults to examine the effect of this intervention type on normal cognition and in healthy processes of aging (Murty et al., 2020).

To control for the risk of bias, PRISMA recommendations for systematic literature analysis have been strictly followed. Studies were independently selected by two different authors, who first analyzed titles and abstracts and subsequently selected the full papers meeting the inclusion criteria, resolving disagreements through consensus. It was not feasible to calculate a reliable risk of bias index, given the high variability and heterogeneity among the studies. This limitation stemmed from the diverse nature of the studies included in the review, which encompassed a wide range of study designs, including case series. The inclusion of heterogeneous populations, interventions, and outcome measures across studies posed challenges

in assessing bias consistently.

3. Results

438 reports have been identified through searches in databases. After removing duplicates, the abstract of 283 studies has been screened, 38 of which have been assessed for eligibility. The total number of studies included in the review is 10: five used tACS as the stimulation methodology, three used GSS, and two used TMS. 22 reports were excluded because of incorrect outcomes or because they were either case reports or study protocols (for more details see Figure 2). Each selected study used a combination of different stimulation types (tACS, NIBS, and TMS), stimulation parameters (e.g., montage, duration of stimulation, duration of treatment), cognitive tasks, global cognition scores (e.g. MoCa, MMSE, ADAS-Cog) and target groups/sub-groups (e.g. AD patients, MCI patients or healthy elderly).

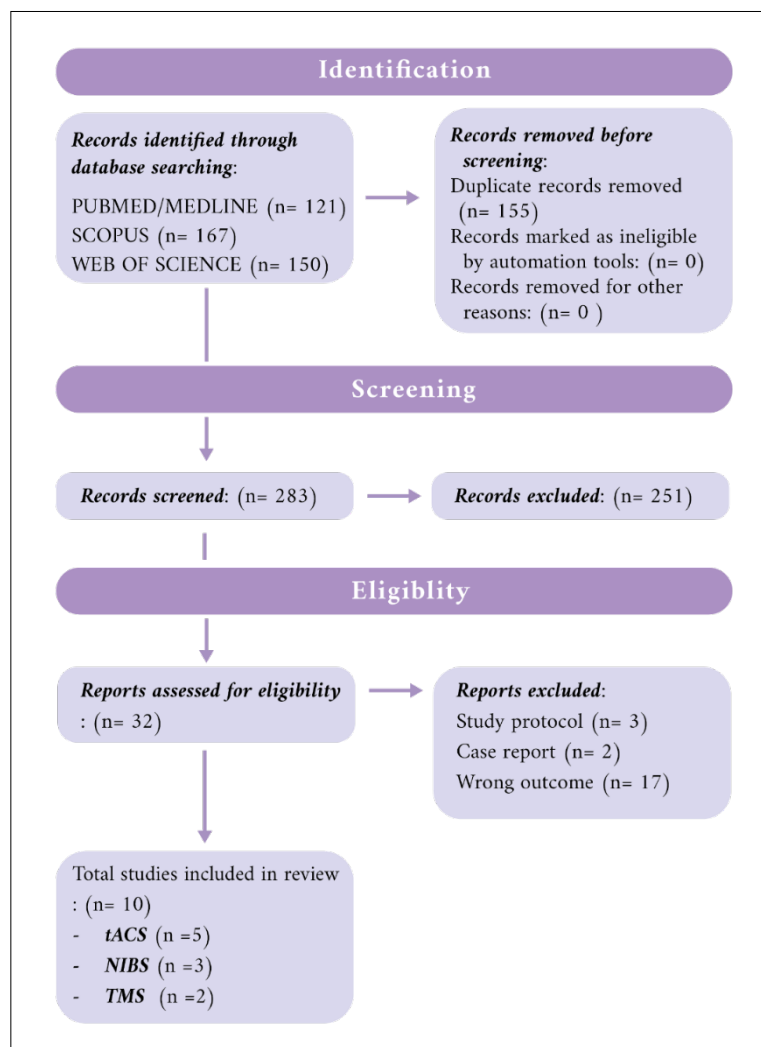


Fig. 2 Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) diagram demonstrating search strategy. Artwork created using Adobe Illustrator v 28.5

A summary of the characteristics of the included studies is presented in Table 1. Given the variability and heterogeneity in study characteristics and outcome measures, a narrative synthesis was judged more appropriate than a meta-analysis. Thus, in line with guidelines by Popay and colleagues (2007), studies were organized by types of stimulation (tACS, NIBS, and TMS) and detailed each study's characteristics were discussed. In this analysis, we focused exclusively on the cognitive performance outcome. For this review, EEG, fMRI, or feasibility data were not examined. The primary scope of this review centers on the examination and interpretation of cognitive performance outcomes derived from the conducted experiments. EEG and fMRI data were not explored as they fall outside the primary objectives of this study. Additionally, feasibility and entrainment data, although pertinent to the practicality and effectiveness of the experimental procedures, were intentionally omitted from our discussion as they do not constitute the central theme of the article. Our emphasis remains on the cognitive aspects of the study, ensuring a focused and coherent analysis within the defined parameters of our research.

Study ID	Samples(S) characteristics	Type of Stimulation (Area of Stimulation)	Misure(S) to assess cognitive functions	Study Design	Main Findings
Benussi et al. (2021)	Main experiment: 60 AD patients (mean age: 72.3, <i>SD</i> = 7.0) Study 1: 12 AD patients Study 2: 12 AD patients	Main experiment and Study 1: tACS (Precuneus) Study 2: (rDLPFC)	Main experiment and Study 2: RAVLT immediate, RAVLT delayed; during the final 20 minutes of stimulation: FNAT (Face-Name Association memory Task) Study 1: Digit Span Backward, Phonemic Fluency, Semantic Fluency, Clock Drawing, TMT-A, TMT-B.	Single session (1 h) of tACS or sham- tACS and, after 1 week, stimulation condition was inverted. Assessment was conducted at baseline and after tACS/sham session.	Main experiment: significant effect of treatment on the RAVLT immediate, RAVLT delayed recall, and FNAT. Study 1: No significant effect of treatment on Digit Span Backward, Phonemic Fluency, Semantic Fluency, Clock Drawing, or TMT-A and TMT-B. Study 2: No significant effect of treatment on RAVLT immediate recall, RAVLT delayed recall, and on FNAT scores.
Kim et al. (2021)	20 MCI patients (mean age: 76.8, <i>SD</i> = 3.2)	tACS/tDCS (DLPFC)	Stroop Color, Stroop Word, TMT- A, TMT-B.	Each participant attended three separate sessions (tACS, tDCS and Sham) for three consecutive weeks (30 min). Assessment was conducted at baseline and after tACS/tDCS/sham session.	Significant effect of tACS treatment on Stroop Color and TMT-B. No significant effect of treatment on Stroop Word and TMT-A.
Sprugnoli et al. (2021)	15 AD patients (mean age: 72) subdivided into three subgroups: Group 1, n = 5 Group 2, n = 5 Group 3, n = 5	tACS (right Temporo- Frontal Lobes or Bilateral Temporal Lobes)	ADAS-Cog, MMSE, MoCa, ADL, Craft Story Recall (Immediate and Delayed), Category Fluency.	Group 1: 2 weeks of unilateral temporo- frontal tACS; Group 2: 2 weeks of bitemporal tACS; Group 3: 4 weeks of bitemporal tACS. Each group received 1 h of daily tACS. Assessment was conducted at baseline and after each tACS session.	No significant changes in overall cognition, memory, and language tasks.
Dhaynaut et al. (2022)	4 AD patients (mean age: 76)	tACS (Bilateral Temporal Lobes)	ADAS-Cog, MMSE, MoCa	4 weeks of tACS session (1 h daily for 5 days a week). Assessment was conducted at baseline and after tACS session	No significant differences in overall cognition
Jones et al. (2023)	13 MCI patients (mean age: 73.62, <i>SD</i> = 5.44)	tACS (F7, F8, FT7, FT8, T7, T8, P7, and P8)	CVLT (SDFR short-delay free recall and LDFR long-delay free recall), PAT, Semantic Fluencies (FAS and animals), IADL.	8 tACS sessions (1 h) in 4 weeks. Assessment was conducted at Week 1 and Week 5.	Significant improvement in the SDFR, and FAS. No significant effect of treatment on LDFR, PAT, semantic fluency (animals), and IADL.
Chan et al. (2022)	15 AD patients (mean age control group: N = 7, mean age = 71.2, <i>SD</i> = 8.2; experimental group: N = 8, mean age = 77.6, <i>SD</i> = 7.5)	GSS (auditory and visual stimulation)	ADAS-Cog, MMSE, MoCa, CDR, FNAT.	Participants were randomly divided in experimental group (N = 8) and sham group (N = 7). 3 months NIBS or sham session (1 h daily). Assessment was conducted at baseline and after NIBS/sham treatment.	No significant changes between groups in MMSE, Moca, ADAS-Cog, and CDR. Experimental group had significant improvement in FNA-DRT.

Lin et al. (2021)	44 healthy participants (mean age: 20.3, $SD = 1.58$)	GSS (visual stimulation)	Digit Span forward and backward, 2-back task	Participants were randomly divided in experimental group and sham group. Single session (1 h) of blue light stimulation (40 Hz) or sham (0 Hz) were performed. Assessment conducted at baseline and after NIBS/sham treatment.	No significant effect of treatment between groups in Digit Span and 2-back test.
Manippa et al. (2024)	36 healthy participants (mean age: 23.30, $SD = 3.91$)	GSS (auditory stimulation)	RAVLT, Digit Span Backward	Each participant attended three separate sessions (40 Hz, 60 Hz, and No stimulation) each lasting 11 min. Memory was assessed during the three conditions.	No significant impact of auditory stimulation on memory performances (RAVLT, Digit Span Backward). Significant effect on RAVLT immediate recall intrusion errors, with higher intrusion rates in no stimulation condition compared to 60 Hz condition. Positive correlations between Digit Span Backward and RAVLT immediate recall in no stimulation condition and 60 Hz condition. Positive correlations between Digit Span Backward and RAVLT delayed recall in 60 Hz condition. Negative correlation between Digit Span Backward and RAVLT immediate recall intrusion errors in 60 Hz condition.
Liu et al. (2022)	37 AD patients (mean age: 67.28, $SD = 7.74$), 41 healthy controls (mean age: 72.08, $SD = 7.30$)	TMS (Bilateral Angular Gyrus)	ADAS-Cog, MMSE, MoCa	AD patients randomly assigned to the experimental and sham group. 4 weeks of treatment (3 times a week for a total of 12 TMS sessions). Assessment was conducted differently between groups. Patients: MMSE, MoCA, ADAS-Cog at pre-treatment, post-treatment, and 8 weeks later. Control group: MMSE, MoCA only once.	Significant effect of treatment in experimental groups in MMSE, MoCa, and ADAS-Cog. Significant treatment effect observed in the experimental group at the 8-week follow-up. Sham group did not exhibit significant changes in cognitive function.
Traikapi et al. (2023)	4 AD patients (mean age: 70.75, $SD = 5.06$)	TMS (Precuneus)	Word Learning list, Semantic association task, Naming task, TMT-A, Corsi, ADAS-Cog	2 weeks of TMS sessions (5 days a week). Assessment was conducted at baseline and after tACS session. Word Learning list, Semantic association task, Naming task, Corsi, and TMT-A were administrated during all sessions. ADAS-Cog was administrated at baseline and post-treatment	No significant effect of treatment on immediate and delayed word learning list, Semantic association task, Naming task, TMT-A, and Corsi. Decrease in total score post-treatment on ADAS-Cog.

Table 1. The table presents a summary of key information extracted from selected studies

3.1 Global cognitive assessment and specific cognitive function tools used in the reviewed studies.

The proposed section focuses on a detailed analysis of the instruments used in all studies included in the review, providing a comprehensive overview of the assessment methodologies employed. Global cognitive assessment and specific cognitive function tests will be examined. Each instrument will be examined in terms of design and validity within the specific scope of the review.

Among studies under review, five experimental investigations included the Montreal Cognitive Assessment (MoCA), Mini-Mental State Examination (MMSE), Alzheimer's Disease Assessment Scale-cognitive subscale (ADAS-Cog), or the Clinical Dementia Rating (CDR) as part of their comprehensive assessment tools among the global evaluation instruments (Chan et al., 2022; Dhaynaut et al., 2022; Liu et al., 2022; Sprugnoli et al., 2021; Traikapi et al., 2023). The MoCA is the one of the most widely utilized screening tools for detecting cognitive impairment. The MoCA is designed to assess various cognitive domains, including memory, attention, language, and visuospatial abilities (Nasreddine et al., 2005). It has a maximum score of 30 points and a lower score may indicate cognitive impairment, especially in the early stages of the disease. It is known for its sensitivity in detecting MCI and is frequently employed in clinical settings for comprehensive cognitive assessments (O'Driscoll & Shaikh, 2017). The MMSE is a brief and widely used cognitive screening tool. It assesses orientation, memory, attention and calculation, language, and visual construction (Folstein et al., 1975). Similar to the MoCA, the MMSE has a maximum score of 30. Compared to the MMSE, the MoCA had been found to meet the criteria for screening tests more effectively in detecting MCI in individuals over 60 years of age, indicating it as a more suitable tool for assessing global cognitive functions (Siqueira et al., 2019; Sokołowska et al., 2016).

The ADAS-Cog, developed for AD clinical trials, focuses on evaluating cognitive functions affected in individuals with Alzheimer's (Mohs et al., 1983; Rosen et al., 1984). It includes tasks related to memory, language, praxis, and other cognitive domains. The total score provides a quantitative measure of cognitive decline, making it a crucial tool in assessing the efficacy of interventions and treatments in research settings. Lastly, the CDR, unlike the aforementioned instruments, is a structured interview-based scale that evaluates multiple domains of cognitive and functional impairment commonly affected by dementia. These domains typically include memory, orientation, judgment and problem-solving, community affairs, home and hobbies, and personal care. The CDR is scored on a scale ranging from 0 to 3, with 0 indicating no cognitive impairment, 0.5 questionable impairment, and scores of 1, 2, and 3 mild, moderate, and severe dementia, respectively (Berg, 1984).

To assess an individual's functional capabilities and level of independence in routine daily activities Sprugnoli et al. (2021) used Activities of Daily Living (ADL) and Jones et al. (2023) utilized Instrumental Activities of Daily Living (IADL) questionnaires. ADL assessment focuses on basic self-care tasks that individuals typically perform on a daily basis. These activities are essential for maintaining personal well-being. Commonly, bathing, dressing, grooming, eating, toileting, and mobility are included. ADL assessments help healthcare professionals estimate a person's ability to carry out these fundamental activities independently. IADL assessments, on the other hand, extend beyond basic self-care tasks to evaluate more complex activities that are crucial for living independently in the community. The IADL questionnaire includes tasks such as cooking, cleaning, managing finances, shopping, using transportation, and handling medications. Assessing IADLs provides insight into an individual's capacity to navigate and function in a more complex and autonomous living environment (Pashmdarfard & Azad, 2020).

Various tools have been employed to assess memory, encompassing a spectrum of cognitive domains. Notably, among the components of memory scrutinized in this review are

episodic memory, associative memory, and working memory.

To measure episodic memory, Benussi et al. (2021) and Manippa et al. (2024) employed the Rey Auditory Verbal Learning Test (RAVLT). This test involves the presentation of a list of 15 unrelated words over five consecutive trials. After each trial, the participant is asked to recall as many words as possible, assessing immediate recall. After a delay, the participant is asked to recall the original list again, assessing delayed recall. The RAVLT provides valuable information about an individual's ability to encode, store, and retrieve verbal information, making it particularly useful in assessing episodic memory functions (Rey, 1942). Changes in performance across trials and the comparison of immediate and delayed recall scores can offer insights into memory processes and potential cognitive impairments. Similarly, Jones et al. (2023) used the California Verbal Learning Test as an instrument designed to evaluate verbal learning and memory. It involves the repeated presentation of a list of words to assess an individual's ability to learn and remember verbal information across different learning trials. The test also includes measures of Short-Delay Free Recall (SDFR) and Long-Delay Free Recall (LDFR), recognition, and the ability to learn and adapt to the structure of the presented verbal material (Delis et al., 2016). Although the RAVLT and CVLT are tests that share significant similarities, the RAVLT is often employed to evaluate memory disorders associated with neurological and psychiatric conditions, while the CVLT is widely used in both research and clinical settings to assess verbal memory and learning strategies, particularly in the context of neurological disorders. The choice between the two depends on specific assessment goals and the preferences of healthcare professionals. Similarly, Traikapi et al. (2023) investigated verbal learning and episodic memory through different forms of the word learning list task, in which participants are presented a list of familiar words and then asked to recall and recognize these words. Their methodology included three distinct learning trials, a delayed recall segment, and a subsequent recognition trial.

To evaluate associative memory Benussi et al. (2021) and Chan et al. (2022) have utilized

the Face-Name Association memory Task (FNAT). FNAT is a cognitive assessment that involves presenting individuals with a set of faces paired with corresponding names (Rentz et al., 2011), and asking them to remember and correctly match the names with the corresponding faces. A similar task is the Paired-Associates Task (PAT), utilized by Jones et al. (2023). It involves presenting pairs of faces and scenes (encoding phase). Subsequently, a face or a scene is shown followed by three items of the other category, and participants select which of the three items was associated with the corresponding stimulus (recall phase). After the recall phase, participants undergo a recognition test where they view pairs of faces and scenes correctly or incorrectly matched and they must indicate if were matched correctly or not. These assessments provide insights into an individual's ability to form and retrieve associations between different type of stimuli, providing a measure of associative memory capabilities.

To measure semantic memory, Traikapi et al. (2023) used alternative versions of the Semantic association task and the Naming task. The first of the two tasks involves presenting a list of images featuring living and nonliving objects categorized into four associative relationships: superordinate, contiguity, part/whole, and function. Participants are required to associate each object with its corresponding use (function relationship), class membership (superordinate relationship), single part (part/whole relationship), and complement (contiguity relationship). It allows to measure participants' ability to associate concepts or words based on their semantic meaning (Caputi et al., 2016). In the naming task, participants are asked to mention the names of different images representing living and nonliving objects, providing a measurement of the knowledge of the object names.

To assess working memory (WM), three studies employed the Digit Span Test (Forward and Backward) (Benussi et al., 2021; Lin et al., 2021; Manippa et al., 2024). In the forward version, participants are presented with a series of digits and are asked to repeat them back in the same order. In the backward version of the task, participants are presented with a series of digits

and are asked to repeat them back in the reverse order (Wundt, 1912). Both versions of the Digit Span Test assess an individual's ability to temporarily hold and manipulate information in their working memory. They are often used in psychological assessments to evaluate cognitive functioning, particularly in the domains of attention and memory. Lin et al. (2021) also employed the 2-back task as a measure of WM. In this task participants are visually presented with a series of numbers and tasked with determining if the current number matched the one presented two steps earlier.

Phonemic Fluency, instead, assesses verbal fluency and executive function. Participants are typically instructed to generate as many words as possible that begin with a given letter within a specific time limit. Similar to Phonemic Fluency, Semantic Fluency evaluates verbal fluency but focuses on generating words within a specific category rather than starting with a particular letter. Participants are asked to produce as many words as possible related to a given category. The Clock Drawing is a cognitive screening test that involves asking individuals to draw a clock face and set the hands to a specific time (Goodglass & Kaplan, 1983). It is often used to assess visuospatial and executive functioning.

Lastly, three studies have assessed executive functions and visual attention, both of which are impaired components in patients with cognitive decline. Benussi et al. (2021), Kim et al. (2021), and Traikapi et al. (2023) employed the Trial Making Test A (TMT-A) and Trial Making Test B (TMT-B). Both are neuropsychological tests that assess visual attention and task-switching abilities (Crowe, 1998). In TMT-A, participants connect numbered circles in ascending order, while in TMT-B, they connect both numbered and lettered circles in an alternating sequence, requiring additional cognitive flexibility. Additionally, Kim et al., (2021) utilized the Stroop test to assess processing speed, attention, and inhibitory control. It is divided into three phases: Color Naming, in which participants are presented with a series of colored rectangles and are asked to name the color of each rectangle as quickly and accurately as possible. This phase

serves as a baseline measure of color naming ability and processing speed. Word Reading, in which participants are presented with a list of color words printed in black ink and are asked to read aloud the words as quickly and accurately as possible. This phase assesses participants' ability to read words without interference from conflicting color information. Color-Word Interference: In this critical phase, participants are presented with color words printed in incongruent ink colors (e.g., the word "red" printed in blue ink) and are asked to name the ink color of each word while ignoring the word itself. This phase measures participants' ability to inhibit the automatic response of reading the word and instead focus on identifying the ink color. Finally, Benussi et al. (2021) used the Clock Drawing test, a cognitive screening test that involves asking individuals to draw a clock face and set the hands to a specific time (Goodglass & Kaplan, 1983). It is often used to assess visuospatial and executive functioning.

3.2 Effects of γ -tACS on cognitive functions

After applying the inclusion criteria, 5 experimental studies using transcranial Alternating Current Stimulation as a treatment were selected. Stimulation montage included: DorsoLateral PreFrontal Cortex (DLPFC), Precuneus, right Temporo-Frontal Lobes, bilateral Frontal Lobes, and a more comprehensive setup involving F7, F8, FT7, FT8, T7, T8, P7, and P8 in accordance with 10–20 EEG system. Three studies included AD patients in their research, while two involved MCI patients.

In the first study under examination, Benussi et al. (2021) employed a single session of γ -tACS targeting the Precuneus to explore the potential improvement in episodic memory performance. This improvement was assessed through the administration of two cognitive tests, the RAVLT and the FNAT. In this randomized, double-blind, sham-controlled, crossover study, 60 AD patients (mean age: 72.3, SD = 7.0) underwent a single session of 1 hour of γ -tACS or sham-tACS and, after 1 week, stimulation condition was inverted (crossover phase). At baseline and after tACS/sham session were administer the Rey Auditory Verbal Learning Test (RAVLT,

immediate and delayed recall) and during the final 20 minutes of stimulation were administered the Face-Name Association memory Task (FNAT, encoding and retrieval phases). Study results suggest a significant influence of a single session of γ -tACS on memory performances. In particular, findings indicate a significant effect of treatment on the RAVL immediate recall ($p < .001$), on the RAVLT delayed recall ($p < .001$), and on FNAT ($p < .001$).

The authors also conducted two additional supporting information studies. In both studies, a single session of γ -tACS or sham tACS was administered, and after one week, the stimulation condition was reversed. In supporting information Study 1, 12 AD participants underwent the stimulation protocol targeting the Precuneus; however, different tests from the main experiment were administered before and after the stimulation/sham sessions. Indeed, the administered tasks included Digit Span Backward, Phonemic Fluency, Semantic Fluency, Clock Drawing, Trial Making Test A, and Trial Making Test B. The results from supporting information Study 1 indicate that there is no significant treatment effect observed in any of the investigated performances: Digit Span Backward ($p = .600$), Phonemic Fluency ($p = .439$), Semantic Fluency ($p = .814$), Clock Drawing ($p = .984$), TMT-A ($p = .500$) and TMT-B ($p = .499$). In supporting information Study 2, 12 AD participants underwent the stimulation protocol targeting the rDLPFC. Similar to the main experiment, the tests employed to assess memory performance included the Rey Auditory Verbal Learning (RAVLT) test for both immediate recall and delayed recall, along with the Face-Name Association Test (FNAT) administered during the last 20 minutes of stimulation. However, the results do not reveal any significant effects of treatment. In particular, no significant effects were shown in RAVLT immediate recall ($p = .942$), RAVLT delayed recall ($p = .983$), and FNAT scores ($p = .588$).

The second study under consideration is conducted by Kim et al. (2021). This research adopted a sham-controlled, double-blind, repeated-measures design, with the order of stimulation interventions counterbalanced among participants. 20 MCI patients (mean age: 76.8, SD = 3.2)

attended three distinct sessions (γ -tACS, tDCS, and Sham) over three consecutive weeks, each lasting for 30 minutes. The target for stimulation was the DLPFC cortex. Both before and after the tACS/tDCS/sham sessions, participants underwent assessments using the Stroop Color and Stroop Word tests, as well as the TMT-A and TMT-B. The study aimed to explore whether both γ -tACS and tDCS would lead to a more substantial improvement in cognitive test performance compared to sham stimulation and whether the extent of enhancement observed in γ -tACS would be superior to that achieved with conventional tDCS. Results showed a significant impact of the intervention on the Stroop color ($p = .004$) and TMT-B ($p = .021$) scores from baseline to post-intervention. Post-hoc comparisons demonstrated a more pronounced change in the Stroop color score following tACS compared to both tDCS ($p = .044$) and sham stimulation ($p = .010$). Additionally, the change in the TMT-B score after γ -tACS was superior to that observed with sham stimulation ($p = .021$). However, there was no significant difference among the interventions concerning alterations in the Stroop word ($p > .050$) and TMT-A scores ($p > .050$).

Another study by Sprugnoli et al. (2021) tested the effect of γ -tACS on cognitive performance in AD patients. By testing different stimulation session durations and electrode positioning on the scalp, the study aimed to investigate the impact of different modalities of γ -tACS on Cerebral Blood Flow (CBF) in specific brain regions. The authors examined potential correlations between alterations in CBF and changes in EEG gamma spectral power with episodic memory scores, which served as an indicator of temporal lobe/hippocampal function. 15 AD participants (mean age: 72.0) received 1 hour of daily gamma tACS for either 2 or 4 weeks in a hospital setting, with cognitive and memory assessments collected before and after the tACS sessions. Depending on the tACS paradigms, participants were grouped into three subcategories: Group 1 (5 AD participants) receiving 2 weeks of unilateral temporo-frontal tACS, Group 2 (5 AD participants) receiving 2 weeks of bitemporal tACS, and Group 3 (5 AD participants) receiving 4 weeks of bitemporal tACS. The ADAS-Cog, MMSE, MoCA and ADL were administered to evaluate any potential changes in overall cognitive functioning. Additionally, the

Craft Story Recall (CSR) Immediate and Delayed tasks, and the Category Fluency task (animals), were used to assess episodic memory and verbal fluency. The results showed no significant changes in overall cognition, memory, and language tests (all p s. $> .050$) in any of the three conditions. Furthermore, Cohen's d effect sizes were calculated for all cognitive tests: ADAS-Cog (Cohen's $d = 0.02$), MMSE (Cohen's $d = 0.21$) MoCA (Cohen's $d = 0.41$), ADL (Cohen's $d = 0.03$), Craft Story Recall immediate recall (verbatim: Cohen's $d = 0.04$; paraphrase: Cohen's $d = 0.03$), Craft Story Recall delayed recall (verbatim: Cohen's $d = 0.28$; paraphrase: Cohen's $d = 0.27$), Category Fluency (Cohen's $d = 0.02$). The trials were conducted as preliminary studies, and the small participant amount may restrict the generalizability and statistical robustness of the findings.

Another study taken into consideration was that of Dhaynaut et al. (2022). The authors published a case series involving 4 AD patients (mean age: 76.0). In this study, γ -tACS targeting Bilateral Temporal Lobes was applied during four weeks of tACS sessions, with each session lasting 1 hour daily for five days a week. The study aimed to investigate the impact of γ -tACS on key neurobiological markers (p-tau and A β load) in AD patients utilizing Positron Emission Tomography (PET). Additionally, the study explored cognitive changes associated with the tACS intervention in the same cohort. The ADAS-Cog, MMSE, and MoCA were administered both at baseline and after the tACS sessions, to assess global cognitive function. No significant changes in overall cognition were observed following tACS treatment, as determined by a Mann-Whitney nonparametric U test (ADAS-Cog $p = .745$; ADL $p = .842$; MMSE $p = .813$; MoCA $p = .725$).

The latest study under analysis is that of Jones et al. (2023). The authors investigated stimulation-related changes in episodic memory, in neurobiological biomarkers, and in induced neuroplasticity. 13 individuals with MCI underwent eight 60-minute sessions of γ -tACS, targeting specific EEG coordinates (F7, F8, FT7, FT8, T7, T8, P7, and P8) based on the 10–20

EEG system. The intervention was conducted over four weeks. The California Verbal Learning Test (CVLT - short-delay free recall (SDFR) and long-delay free recall (LDFR)), Paired-Associates Task (PAT), Semantic Fluencies (FAS and animals), and IADL were administered at Week 1 (baseline) and Week 5 (post-stimulation). Results revealed a significant improvement in Short-Delay Free Recall (SDFR) ($p = .024$) and a non-significant trend for Long-Delay Free Recall (LDFR) ($p = .066$) following eight sessions of gamma tACS. For visual memory, a non-significant trend for accuracy in PAT recall was observed ($p = .083$), while no significant improvement was found in the PAT recognition section ($p = .148$). Verbal fluency, measured by the FAS task, demonstrated a significant improvement in word naming ($p = .049$), driven by a significant gain only in words starting with A ($p = .021$). Lastly, the analysis for Semantic Fluency (animals) indicated no significant improvement following tACS ($p = .861$).

3.3 Effects of GSS on cognitive functions

Following the result screening, three studies utilizing GSS as a stimulation technique were selected. One study employed auditory γ -stimulation, one visual stimulation, and one combined visual and auditory stimulation. Two studies included healthy young participants in their research, while one involved AD patients.

In publishing order, the first study under consideration is that of Chan et al. (2022). The study aimed to investigate exploratory clinical outcomes following three months of chronic daily 40Hz sensory (auditory and visual) stimulation. The authors used a single-blinded, randomized, placebo-controlled design, assigning participants to either the control group (constant light and white noise) or the experimental group (40 Hz light and sound). Stimulation devices were provided for daily use over a six-month period. Unfortunately, the authors were unable to analyze the six-month data due to the COVID-19 pandemic. Fifteen AD patients underwent the stimulation treatment, 7 of them (mean age 71.2, SD = 8.2) were randomly assigned to the control group and 8 (mean age: 77.6, SD = 7.5) were assigned to the experimental group.

Cognitive function was assessed at baseline and after three months. Several participants were excluded, resulting in a reduced sample of 4 participants who completed the experimental condition and 5 participants who completed the control condition. Assessments at baseline and month 3 included MMSE, MoCa, ADAS-Cog, CDR, and FNAT. Results showed no significant differences in global cognitive function outcomes between groups (MMSE: $p = 0.536$; MoCA: $p = 0.198$; ADAS-Cog: $p = 0.237$; CDR Rating: $p = 0.792$). However, the experimental group showed a significant improvement in FNAT accuracy ($p = 0.004$), while the control group exhibited no significant change ($p = 0.528$). The difference in FNAT accuracy between groups was statistically significant ($p = 0.027$).

The second study under consideration investigated the difference in the impact of 40-Hz blue light and 0-Hz light exposure on brain activation and functional connectivity during a recognition memory task. (Lin et al., 2021) Forty-four healthy participants were recruited for the study (mean age = 20.3, SD = 1.58). The participants were randomly assigned to either the experimental group or the sham group. Cognitive assessments, including digit span and 2-back tasks, were administered before and after the stimulation session. Cognitive assessment results indicate a reduction in response times and lower accuracies following optical stimulation compared to data collected before the optical stimulation. However, these differences did not reach statistical significance. A two-way ANOVA was conducted for response time, using the optical stimulation (before and after) as the within-subjects factor and participants in the two groups as the between-subjects factor, revealing no main effect or interaction.

The most recent study under consideration, conducted by Manippa et al. (2024), employed GSS, with a sole focus on auditory stimulation, as a method to investigate differences in cognitive performance. 40 healthy participants (mean age: 23.30, SD = 3.91) enrolled in the study. Each participant underwent three distinct conditions (no auditory stimulation, 40 Hz stimulation, and 60 Hz stimulation) in a counterbalanced order. Declarative memory was

assessed using the Rey Auditory Verbal Learning Test (RAVLT) for both immediate and delayed recall. Working memory was evaluated using the Digit Span Backward. The operationalized variables were Digit Span Backward score, RAVLT immediate recall, RAVLT delayed recall, RAVTL immediate recall intrusion errors and RAVLT delayed recall intrusion errors. Each session lasted 11 minutes during which memory assessments were administered. All three sessions were conducted on the same day, separated by 11 minutes of eyes-closed rest. The total duration of each administration was approximately 60 minutes. Study results did not reveal any significant effects of the auditory stimulation conditions on RAVLT immediate recall, RAVLT delayed recall, and Digit Span Backward. However, findings showed a significant effect on RAVLT immediate recall intrusion errors, with higher intrusion rates in no stimulation condition compared to the 60 Hz condition ($p = .011$). No significant effect was found for RAVLT delayed recall intrusion errors. Pearson's correlations showed a significant positive correlation between Digit Span Backward scores and RAVLT immediate recall in both no stimulation condition ($r = .460$, $p = .005$) and 60 Hz condition ($r = .535$, $p = .001$), but not in the 40 Hz condition ($r = .370$, $p = .068$). Furthermore, a significant positive correlation was observed between Digit Span Backward scores and RAVLT delayed recall in the 60 Hz condition ($r = .353$, $p = .035$). Spearman's correlations indicated a significant negative correlation between Digit Span Backward scores and RAVLT immediate recall intrusion errors ($r = -.381$, $p = .022$), in 60 Hz condition.

3.4 Effects of TMS on cognitive functions

After applying the inclusion criteria, 2 experimental studies using Transcranial Magnetic Stimulation as treatment were selected. Stimulation montage included: bilateral Angular Gyrus and Precuneus. Both studies investigated the effects of TMS on a sample of AD patients.

The first study under consideration is that of Liu et al. (2022). 37 AD patients (mean age: 67.28, SD = 7.74) and 41 healthy controls (mean age: 72.08, SD = 7.30) underwent TMS

targeting the Bilateral Angular Gyrus. AD patients were further randomly assigned to the experimental group and sham stimulation group, while no stimulation was administered to healthy controls. The treatment lasted four weeks, with sessions administered three times weekly (totaling 12 TMS sessions). The assessment protocol differed between the two groups (AD vs healthy controls). ADAS-Cog, MMSE, and MoCA were administered for AD patients at the three time points: pre-treatment, post-treatment, and eight weeks later. In contrast, the healthy controls completed MMSE and MoCA only once. The study aimed to investigate the possibility of rewiring brain connections through the regulation of brain oscillations and explored whether the enhancement of gamma oscillations could improve both local and long-range functional connections within the brain. To achieve this, cognitive assessments were conducted before and after interventions, and neuroimaging analyses, including fMRI and TMS-EEG, were employed to examine the underlying neural processes. Results showed significant enhancements in cognitive functions, as evidenced by increased scores in MMSE and MoCA, as well as reduced scores in the ADAS-Cog, in the experimental group following TMS treatment (all $ps. < .01$). The improvements in clinical symptoms persisted during the 8-week follow-up period (all $ps. < .01$). On the contrary, the sham group did not exhibit significant changes in cognitive function, as indicated by stable MMSE, MoCA, and ADAS-Cog scores.

In the study conducted by Traikapi et al. (2023), the researchers aimed to investigate the effects of TMS applied to the Precuneus region in AD patients. Four participants (mean age: 70.75, SD = 5.06) underwent a comprehensive battery of cognitive assessments. The TMS intervention consisted of daily sessions over a two-week period. Throughout the intervention, participants were evaluated using the Word Learning list, Semantic Association task, Naming task, Corsi, and TMT-A, while the ADAS-Cog was specifically administered at baseline and post-treatment. The primary objective of the study was to investigate whether the TMS treatment could significantly improve performance on episodic memory tasks. Secondary goals included examining improvements in global cognition, semantic memory, spatial memory, and

attention/executive functions. Two types of analyses were conducted: initially, visual analysis utilizing the Percentage Change Index (PCI) for assessing level variations, least squares regression for detecting trend changes, and stability evaluation based on data points within 15% of the mean. Subsequently, in case of positive outcomes from the initial analyses, causal relationships identified prompted randomization tests using effect size indices (Improvement Rate Difference (IRD), and Nonoverlap of All Pairs (NAP)) with a significance level of $\alpha = .05$, ensuring consistency across estimators. The effect size was determined using a Piecewise regression approach. In the review, only the data from the second phase will be discussed and considered. The calculated P values for NAP estimators did not reveal significant evidence of a treatment effect on Immediate Word recall. Visual analysis of Delayed recall and recognition similarly failed to indicate any improvement following treatment. For the TMT-A, the calculated P value for the NAP estimators did not demonstrate a significant treatment effect overall. However, individual NAP indices revealed significant results for Patients 1 (NAP = 0, $p < .05$) and 2 (NAP = .03, $p < .05$). Furthermore, visual analysis did not detect differences in Semantic Association task, Naming task, and Corsi performance before and after treatment. Despite this, all patients exhibited improvement, indicated by a decrease in total score, post-treatment (mean = 28) compared to pre-treatment performance (mean = 33).

4. Discussions

The objective of this review is to investigate the effects of gamma stimulation on cognitive functions. The studies included in this review were divided into three categories based on the type of stimulation employed: transcranial Alternating Current Stimulation (tACS), Gamma Sensory Stimulation (GSS), and Transcranial Magnetic Stimulation (TMS).

Regarding studies using tACS as stimulation methods, two studies have demonstrated the effectiveness of a single session of gamma stimulation in enhancing cognitive performance. In particular, Benussi et al. (2021), investigated the efficacy of a single session of γ -tACS targeting

the Precuneus in episodic memory performance in AD patients. Results indicated a significant improvement in episodic and associative memory performance following γ -tACS intervention. Interestingly, the authors conducted two additional supporting information studies to further explore the effects of γ -tACS on cognitive functions. Supporting information Study 1, targeted the Precuneus and assessed different cognitive functions (attention, memory, verbal fluency and executive functions). However, no significant treatment effects were observed across these tasks. In supporting information Study 2, targeting the rDLPFC, memory tests were conducted, but no significant effects of treatment were found. These findings suggest a specificity of γ -tACS effects on memory performance, particularly when targeting the Precuneus, while other cognitive domains may not be as influenced by this stimulation modality. On the contrary, the study conducted by Kim et al. (2021), underlined the efficacy of 30 minutes of γ -tACS and tDCS targeting the DLPFC on cognitive functions in MCI patients. Results revealed a significant improvement in cognitive test performance, particularly in attention and switching abilities. Notably, the study showed a more pronounced improvement in switching abilities following γ -tACS compared to both tDCS and sham stimulation, suggesting a potentially superior efficacy of γ -tACS in enhancing specific cognitive functions related to executive control. These findings highlight the differential effects of γ -tACS and tDCS on specific cognitive domains and underscore the potential of γ -tACS as a promising intervention for cognitive enhancement also in MCI patients.

Three studies have employed γ -tACS as an intervention tool across multiple consecutive sessions. However, the findings related to cognitive performance outcomes were contrasting, largely due to the significant variability among the studies in terms of stimulation area, intervention duration, and sample size. In particular, the study by Sprugnoli et al. (2021) aimed to explore the effects of γ -tACS on cognitive performance in AD patients by investigating various stimulation parameters and their impact on CBF in specific brain regions. Despite employing different γ -tACS modalities targeting the Precuneus, the results did not demonstrate

significant changes in overall cognition, memory, or language tests. Notably, the small sample size and the exploratory nature of the study limited the generalizability and statistical robustness of the findings, highlighting the need for larger, more definitive trials to elucidate the potential cognitive benefits of γ -tACS in AD. Similarly, Dhaynaut et al. (2022) investigated the impact of γ -tACS targeting the bilateral temporal lobes on neurobiological markers and cognitive function in AD patients. Despite administering γ -tACS sessions over four weeks and assessing global cognitive function using standardized tools such as ADAS-Cog, MMSE, and MoCA, the study did not show significant changes in overall cognition following the intervention. In contrast, Jones et al. (2023) investigated the effects of γ -tACS on episodic memory and verbal fluency in MCI patients. The study revealed a significant improvement in episodic memory and verbal fluencies following eight sessions of γ -tACS. These findings suggest that γ -tACS may hold promise as a non-invasive intervention for enhancing certain cognitive functions in individuals with MCI and AD, although further research is needed to confirm and elucidate its mechanisms of action. At the state of art, while some studies suggest potential cognitive benefits of γ -tACS in neurodegenerative disorders such as AD and MCI, the evidence remains inconclusive, highlighting the need for larger, well-designed trials to better understand its therapeutic potential and optimize stimulation parameters for maximum efficacy.

Three selected studies investigating the effects of GSS on cognitive functions offered valuable insights into the potential cognitive benefits of auditory and visual stimulation techniques, particularly in AD patients and healthy individuals. In the first study by Chan et al. (2022), 6-months daily 40Hz sensory stimulation was administered to AD patients, aiming to explore its impact on cognitive function. Despite the inability to analyze the six-month data due to external factors, results at the three-month mark revealed no significant differences in global cognitive function outcomes between the experimental and control groups. However, the experimental group showed a significant improvement in associative memory compared to the control group, suggesting a potential beneficial effect of sensory stimulation on specific aspects

of cognitive function. Two studies utilized GSS on healthy young participants to examine differences in cognitive performance. These studies aimed to elucidate whether GSS could modulate cognitive processes such as memory and attention in healthy population. In particular, Lin et al. (2021), investigated the impact of 40-Hz blue light exposure on brain activation and functional connectivity during a recognition memory task. While cognitive assessment results indicated a reduction in response times and lower accuracies following visual stimulation, these differences did not reach statistical significance. The study by Manippa et al. (2024) focused solely on auditory stimulation and its effects on cognitive performance in healthy young participants. Results showed no significant effects of auditory stimulation conditions on memory and attention. However, auditory stimulation at 60 Hz was associated with reduced intrusion errors in immediate recall task compared to the no stimulation condition, suggesting a potential role of auditory stimulation in mitigating interference during memory retrieval processes. Overall, while the findings from these studies provide preliminary evidence of the potential cognitive benefits of GSS techniques, further research is warranted to elucidate the underlying mechanisms and optimize stimulation parameters for maximum efficacy, particularly in clinical populations such as AD patients. Additionally, larger, well-controlled studies are needed to confirm and extend these findings, ultimately paving the way for the development of novel therapeutic interventions targeting cognitive dysfunctions.

Finally, the findings from the two selected experimental studies using TMS to target cognitive functions offer valuable insights into its potential therapeutic effects on cognitive functions. In the study conducted by Liu et al. (2022), TMS targeting the bilateral Angular Gyrus demonstrated promising outcomes in enhancing cognitive function among AD patients. Significant improvements were observed in cognitive assessments, as evidenced by increased scores in the MMSE and the MoCA, coupled with reduced scores in the ADAS-Cog. These improvements persisted during the 8-week follow-up period, indicating sustained effects of TMS treatment. In contrast, the study by Traikapi et al. (2023) focused on TMS applied to the

Precuneus region in AD patients, aiming to improve episodic memory and other cognitive domains. Despite the comprehensive battery of cognitive assessments administered, the results did not demonstrate significant improvements in cognitive function following TMS intervention. Both visual analysis and statistical tests failed to provide conclusive evidence of treatment efficacy across various cognitive tasks, including immediate and delayed word recall, recognition, semantic memory, spatial memory, and attention/executive functions. Overall, the contrasting findings from these studies underscore the importance of careful consideration of stimulation parameters, target brain regions, and study designs in TMS interventions for cognitive enhancement in AD patients. Further research is warranted to elucidate the optimal protocols and mechanisms underlying TMS-induced cognitive improvements in neurodegenerative disorders like AD.

5. Conclusion

Gamma oscillation modulation through tACS, GSS, and TMS shows potential benefits for cognitive enhancement in patients with AD and MCI. Each technique has demonstrated specific capabilities in entraining brain oscillations and improving various cognitive domains. tACS has shown efficacy in enhancing episodic memory and attention abilities, especially when targeting the Precuneus and the DLPFC (Benussi et al., 2021; Kim et al., 2021). GSS, utilizing rhythmic sensory stimuli such as 40 Hz light flicker or auditory tones, has evidenced significant improvements in associative memory and attention tasks, demonstrating good tolerability in patients (Chan et al., 2022; Lin et al., 2021). Lastly, TMS has shown promise in enhancing functional connectivity and overall cognitive performance, with notable improvements in memory and executive functions when targeting the Angular Gyrus and the Precuneus (Liu et al., 2022). The integration of these techniques with real-time EEG monitoring can optimize therapeutic outcomes, offering personalized and non-invasive approaches to addressing cognitive decline associated with AD and MCI.

5.1 Limitations

Several limitations need to be acknowledged in this review due to the inherent heterogeneity among the studies included. Firstly, the small sample sizes across various studies limit the generalizability and statistical power of the findings. Additionally, there is substantial variability in stimulation types, including tACS, NIBS, and TMS, each with its own unique mechanisms and effects on brain activity. Furthermore, differences in stimulation parameters such as montage, duration of stimulation, and duration of treatment contribute to the complexity of comparing results across studies. Moreover, the cognitive tasks utilized varied widely among studies, making it challenging to directly compare cognitive outcomes. Additionally, the use of different global cognition scores, such as the MoCA, the MMSE, and the ADAS-Cog, further complicates the synthesis of findings. Lastly, the target groups or sub-groups under investigation, including AD patients, MCI patients, or healthy elderly individuals, introduce additional variability and potential confounders into the analysis. The high heterogeneity of the studies made it unfeasible to calculate the risk of bias, limiting our review in terms of its ability to assess the reliability and validity of the included studies. Therefore, while this review provides valuable insights into the effects of various stimulation techniques on cognitive function, caution must be exercised when interpreting and generalizing the results due to these inherent limitations and variations among the included studies.

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CONCLUSIONS

Through the presentation of five studies, this doctoral thesis adopts an integrated and multidisciplinary approach to investigate the cognitive, emotional, and behavioral dimensions of aging, emphasizing their implications for health and well-being in older adults.

The study presented in Chapter 1 examined the effects of facial occlusion on emotion categorization and identity recognition across younger and older adults. Results revealed that occluded stimuli impaired emotion detection significantly more in older adults but did not affect their ability to recognize previously encountered faces. These findings underscore distinct cognitive processes for emotion recognition and identity processing, while also highlighting the resilience of certain memory functions in aging. The lack of an age-related decline in identity recognition for occluded faces, combined with improved performance for occluded compared to whole faces, supports theories emphasizing the differential impact of partial occlusion on facial processing tasks. This resilience could be attributed to adaptive processing strategies or increased attention allocation to detect facial features during learning. The enhanced recall of occluded faces offers insights into compensatory mechanisms, which warrant further exploration to optimize communication across everyday scenarios.

The study in Chapter 2 explored the neural pathways of emotion processing, focusing on cortical and subcortical routes in younger and older adults. Findings demonstrated that although older adults exhibited a general decline in perceptual performance, no specific impairment in these pathways emerged. Notably, the absence of age differences in performance for hybrid and Low Spatial Frequencies (LSF) stimuli challenges the hypothesis of weaker subcortical activity in older adults, suggesting a more intricate interplay between cortical and subcortical pathways. Furthermore, older adults' comparable performance for upright angry faces in unfiltered and High Spatial Frequencies HSF conditions supports the idea of a preserved ability to process

proximal emotions via the cortical route. The preserved face-inversion effect in both age groups further supported the robustness of global face processing mechanisms across the lifespan, highlighting the stability of visual and emotional processing systems despite the effects of aging.

Chapter 3 addressed the "positivity effect" in activity scheduling, revealing that older adults tend to plan positive activities closer in time while postponing negative ones, compared to younger adults. This behavior aligns with Socioemotional Selectivity Theory (SST), suggesting that older adults prioritize emotional well-being by focusing on positive experiences. The association between negative affect and the tendency to schedule positive activities sooner in older adults highlights a potential adaptive strategy to mitigate emotional distress. Conversely, the greater impact of negative valence on older adults, likely due to cognitive resource limitations described by the Selective Selectivity Theory, further reinforces their tendency to postpone cognitively and emotionally challenging activities. These insights can guide interventions to promote healthier emotional regulation strategies in aging populations.

In Chapter 4, the complex relationship between aging, cognitive biases, and temporal processing was explored. Results showed that while systematic errors in time estimation were consistent across all age groups, older adults exhibited pronounced difficulties in the bisection task. Specifically, older adults overestimated intervals more than other groups in the bisection condition, likely reflecting the heightened cognitive load and reduced working memory efficiency. This study highlights the importance of understanding the interplay between cognitive load and temporal processing in aging, suggesting that targeted interventions to enhance attentional and working memory resources may mitigate these deficits.

Finally, Chapter 5 investigated the potential of gamma oscillation modulation techniques to address cognitive impairment in Alzheimer's Disease (AD) and Mild Cognitive Impairment (MCI). Findings from a systematic review highlighted the promise of these non-invasive methods, with evidence suggesting that γ -tACS can enhance episodic memory and executive

functions, particularly when targeting specific brain regions like the Precuneus. Gamma Sensory Stimulation (GSS) showed preliminary benefits in associative memory but lacked consistent effects on global cognitive functions, while TMS demonstrated potential for sustained cognitive improvement in AD when applied to the Angular Gyrus. Although these results are encouraging, the variability in outcomes highlights the need for standardized protocols and larger-scale trials to confirm therapeutic efficacy and optimize clinical applications.

Taken together, these studies provide a comprehensive perspective on the interplay of cognitive, emotional, and behavioral factors in aging. From a theoretical standpoint, they contribute to a deeper understanding of age-related changes in emotion processing, decision-making, and temporal cognition. From a practical standpoint, they inform the development of interventions to promote healthy aging and address cognitive decline in older adults.

This doctoral thesis highlights the importance of tailoring interventions to individual differences in cognitive and emotional processing. For example, the observed positivity bias in older adults' activity scheduling could be leveraged to design interventions promoting emotional well-being, while insights from studies on temporal processing can inform strategies to enhance cognitive performance under time constraints. Additionally, the promise of gamma modulation techniques offers a potential avenue for mitigating the effects of neurodegenerative diseases, paving the way for innovative approaches in clinical neuropsychology.

In conclusion, the findings presented in this thesis advance scientific knowledge on the cognitive and emotional dimensions of aging, with implications for health and practical interventions. By shedding light on these complex processes, this work aims to contribute to the development of effective strategies to enhance the quality of life and cognitive health of older adults in an aging global population.