FACE PERCEPTION IN AGING: EFFICIENCY, NOISE & ORIENTATION

EFFECTS OF AGING ON FACE PERCEPTION: EXPLORING EFFICIENCY, NOISE & ORIENTATION

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Lay Abstract

Our experience of the visual environment results from perceptual processes in the brain. Many of these processes change with age, such as our ability to identify someone from a photograph of their face. Performance is influenced by both random variability, or "noise", within the observer and how efficiently we use task-relevant information in the visual environment. By systematically manipulating the amount of available stimulus information I assessed the contribution of these factors to older adults' judgements of facial identity, and characterized the information on which these decisions are based. These experiments are the first to consider how face perception in older adults is constrained by the combined effects of internal noise and the efficiency with which the visual system utilizes various sources of information. The results provide a number of directions for future research in the fields of face perception and age-related changes in complex pattern vision.

Abstract

Face perception is impaired in a variety of ways in older adults, but the mechanisms underlying these changes remain unclear. A central theme of this dissertation is that task performance is constrained by two factors intrinsic to the observer: sources of random variability – internal noise – and the efficiency with which task-relevant stimulus information is utilized. This thesis uses several behavioural, psychophysical methods to examine how age-related changes in one or both of these factors affect face processing. Chapter 2 used the classification image (CI) method to characterize the spatial sampling patterns of younger and older observers performing a face discrimination task. Compared to younger adults, older adults used information in the eye/brow region less consistently and instead relied on relatively less informative regions such as the forehead. The differences in CIs accounted for the lower absolute efficiency that was found in older observers. Chapter 3 estimated internal noise and calculation efficiency by measuring threshold-vs.-noise (TvN) curves and response consistency in a face discrimination task. Compared to younger observers, older observers had higher additive internal noise and lower calculation efficiency, but the magnitude of multiplicative internal noise did not differ between age groups. Previous studies have shown that younger adults have a bias to rely on horizontal structure to discriminate and identify faces, and the magnitude of this so-called horizontal bias is correlated with identification accuracy. The experiments in Chapter 4 measured horizontal bias in younger and older adults, and found that age differences in horizontal bias account for some, but not all, of the age difference in face identification accuracy. In summary, my work demonstrates that additive (but not multiplicative) internal noise is greater in older adults, and that they are less efficient at sampling information that is conveyed by structure at different locations and orientations in a face.

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Take good care, everyone.
S.

In the midst of winter, I at last discovered that there was in me an invincible summer.
– *Albert Camus*

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Chapter 3: Contribution of internal noise and calculation efficiency to older adults' face discrimination
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Chapter 4: Age-related changes in orientation bias for face identification
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Chapter 5: General Discussion

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Chapter 1

General Introduction

The experiments comprising this thesis examine the mechanisms underlying complex pattern vision and how these mechanisms are influenced by healthy aging. Specifically, this dissertation focusses on developmental changes in the perception of higher-order, socially relevant stimuli – human faces. In this introductory chapter, I begin by outlining several age-related changes in the visual pathway. I then provide a brief review of age-related changes in face perception, and outline several theories used to explain these changes. Next, I cover the general framework and key concepts used throughout the thesis data chapters. Finally, I explain the motivation for the experiments in each data chapter, and provide a summary of the relevant findings.

1.1 Age-related changes in the visual system

The human visual system is a complex network of optical and neural structures and processes that contribute to our experience of the world as a stable, cohesive visual environment. Research in visual perception attempts to characterize how information is represented by various components of the system, conveyed to higher level visual processes, and integrated into a meaningful percept. Even healthy older adults exhibit deficits in several aspects of visual processing, including: contour integration (Del Viva and Agostini, 2007; McKendrick et al., 2010; Roudaia et al., 2008), figure-ground segregation (Lass et al., 2017), symmetry detection (Herbert et al., 2002) and the perception of complex novel shapes (Pilz et al., 2011) and everyday objects such as watches (Meinhardt-Injac et al., 2014), faces (Boutet and Faubert, 2006; Habak et al., 2008), and bodies (Ruffman et al., 2009). While optical factors, such as hardening and opacification of the lens, constriction and inelasticity of the pupil, and accumulation of intra-ocular debris (Owsley, 2011; Spear, 1993; Weale, 1963) undoubtedly contribute to age-related deficits, they cannot fully account for the effects of aging. This suggests that neural factors also significantly contribute to age-related impairments in pattern vision (Sekuler and Sekuler, 2000).

1.2 Age-related changes in face processing

Human faces are ubiquitous, socially relevant stimuli that we encounter from birth (Mondloch et al., 1999). Despite significant homogeneity across human faces, our subjective experience is that we extract diagnostic information for gender, expression, attentional direction (e.g., eye gaze, viewpoint), trustworthiness, ethnicity, age, and identity with relative ease and efficiency. However, age-related deficits in face processing are common: eye-witness identification (Searcy et al., 1999), detecting subtle changes in the spacing (Chaby et al., 2011; Slessor et al., 2013) and orientation (Murray et al., 2010) of facial features, ignoring irrelevant context (Boutet and Meinhardt-Injac, 2019; Konar et al., 2013; Meinhardt-Injac et al., 2014), identifying faces varying in viewpoint (Adduri and Marotta, 2009; Habak et al., 2008) or expression (Ruffman et al., 2008), and interpreting social cues (Halberstadt et al., 2011) are all disrupted in older adults.

These declines in face perception cannot wholly be explained by changes in the optics of the eye (Bennett et al., 1999; Bieniek et al., 2013; Owsley et al., 1981), a general decline in non-face object recognition (Boutet and Faubert, 2006; Hildebrandt et al., 2013; Meinhardt-Injac et al., 2014), or a general cognitive decline (Hildebrandt et al., 2011). Instead, the age-related decline in face perception seems to be due, at least in part, to a change in face-specific neural processes. Although well established in the literature, the cause of these age-related changes remains unclear: Possible explanations include increased false alarms to unfamiliar faces (e.g., Bartlett and Fulton, 1991; Searcy et al., 1999), reduced processing speed (e.g., Rousselet et al., 2009), neurophysiological changes (e.g., Burianová et al., 2013), impaired configural/holistic processing (e.g., Chaby et al., 2011), and deterioration in the ability to selectively use perceptual information (e.g., Hashemi et al., 2019; Owsley et al., 1981). These explanations are not necessarily mutually exclusive, and a full characterization of age-related deficits in face processing naturally requires consideration of multiple theoretical and experimental paradigms. Below, I expand upon two of these; however, this thesis does not aim to directly compare frameworks. My experiments are presented within the context of a well established perceptual information processing framework, grounded in knowledge about basic physiological and neural processes whose functions are hypothesized to change with aging.

1.3 Holistic and configural processing

Our extensive experience with faces, the observation that certain manipulations have a larger effect on faces than other complex non-face objects, and the existence of face-specific neural responses, have led some to suggest face perception may rely on processes that differ qualitatively from those that underlie non-face, object perception (see Maurer et al., 2002 for a review; but see Sekuler et al., 2004; Gaspar et al., 2008b; Konar et al., 2010 for an alternative view). In this framework, normal processing of upright faces requires observers to encode the face as a unified, integrated whole (i.e., holistic processing) and/or encode the spatial relations among facial features (i.e., configural processing)[1]. On the other hand, faces presented in less familiar contexts (e.g., upside-down, misaligned halves, isolated facial features), as well as other complex non-face objects (e.g., houses, cars, animals) are thought to be processed using a more local, part-based analysis. For example, a common measure of holistic processing is the Composite Face Effect (CFE), in which observers are slower and less accurate at discriminating the top half of a face when it is aligned with the task-irrelevant bottom half of the face compared to when the top and bottom are misaligned (Young et al., 1987). That the task-irrelevant context (bottom halves) influences performance is taken as evidence that humans unavoidably integrate information over the entire face. Further, this effect is diminished by inversion, and the size of these holistic effects are less strong for non-face stimuli (Hole, 1994; Young et al., 1987).

Regardless of whether holistic processing is innate (Farah et al., 1998; Kanwisher, 2000) or mediated by experience (Gauthier et al., 1998), it is generally believed that greater reliance on holistic processing has a facilitative effect on task performance and ought to be associated with better upright face identification (though see Konar et al., 2010). Thus, one explanation for age-related deficits in face perception is that older

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[1] Throughout this thesis I will use the terms holistic and configural interchangeably to refer to hypotheses suggesting face and object perception are qualitatively different.

adults make less efficient use of holistic processing. Some aging studies support the notion of impaired configural or holistic processing in older relative to younger adults (Chaby et al., 2011; Murray et al., 2010; Schwarzer et al., 2010; Slessor et al., 2013) while others find either no change (Boutet and Faubert, 2006) or even an increased reliance on this type of processing (Adduri and Marotta, 2009; Daniel and Bentin, 2012; Konar et al., 2013). In addition, Konar et al. (2013) found an age-related deficit in face identification accuracy even though holistic processing – as measured by the CFE on reaction times – was larger in older adults. In sum, these findings suggest a holistic processing account is unable to provide a complete picture of age-related declines in face perception, and that a different approach might be required.

1.4 Information processing efficiency

1.4.1 Spatial domain

Eye-tracking studies have shown that observers demonstrate a characteristic spatial sampling profile for human faces, with a tendency to make repeated transitions between the eyes, nose, and mouth, in a "T" shaped pattern when viewing faces (Yarbus, 1967). Subsequent studies confirmed the importance of these regions to encoding and recognition memory for faces (Henderson et al., 2005), and different scanning patterns are common in populations who have difficulty with face identification (Bobak et al., 2017; Schwarzer et al., 2007; de Xivry et al., 2008; Hernandez et al., 2009; Papagiannopoulou et al., 2014; Sterling et al., 2008; Delerue et al., 2010; Kathmann et al., 2003), including older adults (Heisz and Ryan, 2011; Murphy and Isaacowitz, 2010; Sullivan et al., 2007; Wong et al., 2005; Firestone et al., 2007; Chan et al., 2011; Proietti et al., 2015; Chan et al., 2018; Chaby et al., 2017).

The results of psychophysical studies measuring discrimination thresholds, as opposed to eye movements, suggest that the eye/brow region seems to be particularly important for face discrimination and identification in younger adults (Sekuler et al., 2004; Gold et al., 2004; Gosselin and Schyns, 2001; Schyns et al., 2002), and several eye-tracking studies have explored the hypothesis that age-related deficits result from different or less efficient sampling of the eye/brow regions. Heisz and Ryan (2011) found that repeated exposure to a given facial identity affected the pattern of spatial sampling in younger, but not older, adults. Specifically, as faces became more familiar, younger adults made fewer fixations within faces, and increased the relative proportion of time spent fixating informative (e.g., eyes) versus less informative (e.g., nose, mouth) regions, whereas older adults showed no change in their distribution of fixations, and spent more time fixating less informative regions such as the nose. Facial expressions of anger, fear, and sadness are often considered “top” emotions because diagnostic information is heavily concentrated in the upper-half of the face, and some studies show that older adults spend proportionately less time looking toward the upper- than lower-halves of these emotional faces compared to younger adults (Murphy and Isaacowitz, 2010; Wong et al., 2005). Further, this age difference in gaze pattern is correlated with identification accuracy on at least some of these emotions (Murphy and Isaacowitz, 2010; Sullivan et al., 2007; Wong et al., 2005), supporting the notion of an age-related deficit in spatial sampling of the eye region. On the other hand, Firestone et al. (2007) found that older adults make *more* eye movements between inner facial features (such as the eyes) than do younger adults: however, this pattern of scanning resulted in *worse,* not better, facial identity recognition memory in the older age group. Similarly, using a gaze-contingent paradigm, Chan et al. (2011) demonstrated older observers’ performance was not improved by yoking their eye movements to those of younger observers. These last two results suggest gaze fixation may not provide a complete account of the visual information driving older observers’ decisions in face perception tasks.

Psychophysical techniques have been developed that can supplement the results of eye movement studies. The response classification technique measures the association between the contrast at various (potentially all) spatial and temporal locations within a stimulus and the decisions made by an observer in a discrimination task (Ahumada Jr, 1996; Beard and Ahumada Jr, 1998). In a typical response classification experiment, on each trial a unique external noise field is generated and added to one of two randomly chosen signals (e.g., Face A or Face B), and the observer’s task is to assign it to a stimulus class (e.g., Face A or Face B). When signals are embedded in a high level of external noise, on some trials, by chance, the external noise will be distributed in such a way to either amplify or deemphasize certain characteristics of a given face (e.g., Face A), leading the observer to be either more or less likely to make a Face A classification, respectively. By correlating responses with the noise contrast at each spatial and/or temporal location, one can create a map of the stimulus structure driving an observer’s decision. Using this and related response classification techniques (e.g., Bubbles), numerous authors have shown that younger observers rely on a highly spatially localized region around the eyes/brows to identify faces (Sekuler et al., 2004; Gold et al., 2004; Gosselin and Schyns, 2001; Schyns et al., 2002). In Chapter 2, I apply a variant of this technique (Nagai et al., 2013) to compare face discrimination in older and younger adults.

1.4.2 Fourier domain

Face identification in younger adults relies on information conveyed by a narrow band of spatial frequencies (Boutet et al., 2003; Costen et al., 1996; Gaspar et al., 2008a; Gold et al., 1999a; Näsänen, 1999; Willenbockel et al., 2010) and orientations (Dakin and Watt, 2009; Goffaux and Dakin, 2010; Pachai et al., 2013, 2018) that are spatially localized to the eye/brow region (Sekuler et al., 2004; Gold et al., 2004; Gosselin and Schyns, 2001; Schyns et al., 2002). Thus, to the extent that older observers have less selective visual mechanisms, we might expect difficulties processing this information in faces and therefore see decrements in performance. Neurons in primary visual cortex (V1) are selective for orientation and spatial frequency (Hubel and Wiesel, 1962, 1968; De Valois et al., 1982a,b), and neurophysiological evidence in monkeys and cats (Hua et al., 2006; Schmolesky et al., 2000; Yu et al., 2006) suggest that these neurons may become more broadly tuned (i.e., less selective) with age. On the other hand, psychophysical studies in older human adults have suggested virtually no change in spatial frequency or orientation tuning (Delahunt et al. 2008; Govenlock et al. 2009, 2010; but see Pilz et al. 2020). However, these experiments used simple stimuli (e.g., gratings), and larger age differences may be found with more complex stimuli and/or tasks that engage more complex cortical networks (Faubert, 2002; Habak and Faubert, 2000).

Spatial frequency and orientation are processed in primary visual cortex, but reduced selectivity at that stage presumably degrades the signal further up in the visual hierarchy as the stimulus representation becomes more complex. Several studies have examined how the orientation bias for face identification changes during healthy aging (Obermeyer et al., 2012; Goffaux et al., 2015; Schaich et al., 2016; Obermeyer et al., 2017) and in older adults with central visual field loss (Yu and Chung, 2011). Like younger observers, older adults preferentially rely on horizontal facial structure over other orientations when judging the identity of unfamiliar (Goffaux et al., 2015; Obermeyer et al., 2012) and familiar (Yu and Chung, 2011) faces, and some evidence suggests this orientation bias may be stronger in upright than inverted faces (Goffaux et al., 2015, though see Obermeyer et al., 2012). However, it remains unclear whether reduced horizontal bias *per se* is the reason that face identification is worse in older than younger adults. I examine this hypothesis in Chapter 4.

1.5 Modelling human behaviour

In vision science, we often characterize and measure an observer's decision process and sensitivity in a task using the signal detection framework (Green et al., 1966; Macmillan and Creelman, 2005). Consider a typical discrimination task where an observer must decide which of two randomly selected signals was shown (e.g., Face A or Face B). On each trial, the stimulus evokes an internal response in the observer, who then compares it to some criterion in order to decide which face was presented. One underlying principle of signal detection theory is that internal variability, or "noise", results in internal responses that are probabilistic: a given stimulus is associated with a *distribution* of internal responses (Barlow, 1956, 1957; Green, 1964). In other words, an observer limited by internal noise must decide if the internal response on an individual trial was drawn from the distribution associated with Face A or Face B[2]. Differences in task performance among individuals, groups, or stimulus conditions are assumed to reflect differences in the variances or means of the internal distributions. For example, bringing the means closer together will result in distributions that overlap more, decreasing the probability of a correct decision. Similarly, holding the mean difference constant while increasing variance will increase the overlap of the two distributions, again decreasing the probability of a correct decision. Thus, in the signal detection framework, an observer's sensitivity, d', is determined by the ratio of signal (distance between the distributions) to noise (standard deviation of the distributions) within an observer. The research in this thesis uses a framework in which the magnitude of the signal-to-noise ratio is constrained by both the efficiency with which an observer uses task-relevant stimulus information (often referred to as *sampling* or *calculation* efficiency) and the sum of the variances of external and internal sources of noise that affect the distributions of the decision variable.

Calculation efficiency is a measure of how much stimulus information is encoded by deterministic (i.e., non-random) computations that transform the stimulus input

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[2] Often it is assumed that the two distributions are equal-variance Gaussians with different means.

into a decision variable. In many perceptual tasks the optimal strategy is to apply a linear filter, or template, that is matched to the spatial and temporal characteristics of the stimulus (Eckstein and Ahumada, 2002; Gold et al., 2004; Murray et al., 2002). An ideal observer computes a cross-correlation between the stimulus and each of the possible signals, and selects the option yielding the largest value. Human observers employ non-optimal computations, and the more an observer deviates from an ideal strategy, the worse their performance. For example, a human observer might use a template with a spatial frequency or orientation bandwidth that is broader than the stimulus bandwidth, and which therefore will pass more noise than the ideal template, resulting in poorer performance. In the context of face perception, an observer might use a template that samples a relatively less informative face region for face identification (e.g., chin), and/or ignore more informative regions (e.g., eyes). This type of inefficiency would be consistent with an age-related change in spatial sampling, as observed in the eye-tracking studies mentioned above. Bennett et al. (1999) found an age-related decrease in efficiency for detecting sine wave gratings embedded in noise: older observers were less efficient than younger observers.

Internal noise refers to stochastic (i.e., random) variability within the system, and also degrades performance relative to ideal. For an observer limited by internal noise, which causes trial-to-trial response variability, repeated presentations of a physically identical stimulus presented at two different times will produce a distribution of internal responses, rather than the same response each time (Burgess and Colborne, 1988; Green, 1964; Spiegel and Green, 1981). The variance of this distribution is determined by the magnitude of an observer's internal noise at the level of the decision variable. On the other hand, an ideal observer typically has no internal noise, and therefore performance is limited only by the available stimulus information and any existing external noise. Such an observer will always make the same decision, whether correct or incorrect, on repeated presentations of the stimulus and noise, and therefore exhibit perfect response consistency. Possible sources of internal noise include random variability in spontaneous rates of neural firing (Carandini, 2004; Tolhurst et al., 1981; Vogel et al., 2005; Vogels et al., 1989) and fluctuations in response criterion across trials (Burgess, 1990). Physiological studies in senescent animals have shown increased rates of spontaneous firing for neurons selective to orientation and spatial frequency (Hua et al., 2006; Schmolesky et al., 2000; Yu et al., 2006), and psychophysical studies have found that higher levels of internal noise in older humans contribute to age differences in motion detection (Bennett et al., 2007) and discrimination (Bower and Andersen, 2012), direction identification (Bennett et al., 2007; Bogfjellmo et al., 2013), orientation discrimination (Betts et al., 2007), and detection of sine wave gratings at high (10 cpd) spatial frequencies (Pardhan, 2004). My thesis examines whether this is true for older adults' face discrimination.

One way to differentiate between the effects of internal noise and efficiency is to measure thresholds for signals embedded in different levels of external visual noise to obtain a threshold-vs.-noise (TvN) masking function. This noise-masking function follows the form $E = k(N + N_{eq})$ for a wide range of tasks, including face discrimination. The parameter N_{eq}, or equivalent input noise, is the amount of external noise that must be added to the signal in order to double an observer's threshold in the absence of external noise. The parameter k is the "effective signal-to-noise ratio" (Pelli and Farell, 1999; Pelli and Blakemore, 1990; Pelli, 1981), and it's reciprocal, (1/k), is variously termed high-noise efficiency, sampling efficiency, or calculation efficiency. The TvN function separates all factors that contribute to human performance into two sources: one that has a constant effect across all levels of external noise, and another part that has an effect which increases with increasing external noise. In Chapter 3, I use noise-masking to separate the influence of each parameter on face discrimination and see if N_{eq} and k vary as a function of age.

The results of this thesis are interpreted in the context of Pelli's early-noise Linear Amplifier Model (LAM; Pelli, 1981; Pelli and Blakemore, 1990) to conceptualize an observer's decision process. An observer forms an internal representation of a stimulus received by the visual system (e.g., a face), possibly masked with white, Gaussian visual external noise. Next, an internal noise that does not vary with respect to stimulus magnitude (i.e., contrast-invariant or -independent) is added to this representation. In the Pelli model, this is referred to as *additive* internal noise. The observer then performs a contrast-invariant computation on this information. A decision is then made by comparing the output of this system to some decision criterion.

As with any model, the LAM makes a number of assumptions. First, it assumes that an observer is linear, which clearly is an over simplification. Also, the model assumes the variance of the internal noise is independent of the contrast of the stimulus rather than varying with the contrast of the input (Burgess and Colborne, 1988; Tolhurst et al., 1983). Fortunately, psychophysical techniques have been developed that can measure contrast-dependent internal noise (Burgess and Colborne, 1988; Green, 1964;

Spiegel and Green, 1981), and in Experiment 2 of Chapter 3 I use a variant of Pelli's model to measure this type of noise. The LAM also assumes that the calculation is contrast-invariant, but Allard and Cavanagh (2011) have shown it might depend on how stimuli are masked with external noise. Finally, the LAM places all internal noise *before* the calculation (i.e., early-noise), whereas others (for a review see Lu and Dosher, 2008) have developed models that are late-noise, which under some circumstances changes the interpretation of results. I will address these issues at several points in the experimental chapters and in the general discussion (Chapter 5). Despite these simplifying assumptions and potential problems, the LAM adequately accounts for TvN curves measured in a wide range of tasks (Bennett et al., 1999; Gold et al., 2005; Legge et al., 1987; Pelli, 1981; Pelli and Farell, 1999; Tjan et al., 1995), including face perception in younger adults (Albonico et al., 2018; Christensen et al., 2013; Gaspar et al., 2008b; Gold et al., 1999b, 2004; Shafai and Oruc, 2018).

1.6 Thesis overview

Several studies have considered how differences in internal noise and calculation efficiency contribute to age differences in visual performance in grating detection and discrimination tasks (Allard et al., 2013; Bennett et al., 1999; Betts et al., 2007; Pardhan, 2004; Yan et al., 2020). Faces, however, are more complex patterns that may engage special, face-specific mechanisms, and therefore it is unclear whether age-related changes in face perception are related to changes in efficiency or internal noise. The main goal of this thesis was to examine the role played by these factors in face discrimination in older and younger adults (Chapter 3), and to explore possible sampling inefficiencies in selective processing of information in the spatial (Chapter 2) and orientation (Chapter 4) domains.

In Chapter 2 I measure classification images (CIs) to explore how younger and older adults sample visual information from a face during a discrimination task. The spatial structure of younger observers' CIs was concentrated near the eyes and eyebrows, suggesting pixels in that region consistently influenced their decisions. On the other hand, older observers' CIs differed qualitatively: two showed spatial structure similar to younger observers, yet also relied on relatively less informative regions, such as the forehead and mouth, and many older observers had no readily apparent structure in their CIs. Older adults had higher face discrimination thresholds and lower absolute efficiency – as indexed by the cross-correlation between observers' CIs and the ideal template of a linear discriminator – compared to younger adults. Critically, discrimination thresholds and absolute efficiency were strongly and similarly correlated in both age groups, suggesting that, despite the lack of observable structure in older adults' CIs, this method captures between-subject differences in older adults' perceptual strategy.

In Chapter 3, I use the equivalent input noise and response consistency paradigms to address the degree to which older adults' face discrimination is affected by internal noise and calculation efficiency. Experiment 1 indicated both additive internal noise and high-noise efficiency contribute to older adults' higher face discrimination thresholds. In Experiment 2, older and younger observers had similar internal-to-external noise ratios, as indicated by the lack of an age difference in the slopes of the response consistency functions. This suggests multiplicative internal noise did not significantly contribute to efficiency in Experiment 1, and rules out the contribution of internal noise to the lack of observable structure in older adults' CIs in Chapter 2.

In Chapter 4, I test whether age differences in observers' preferential reliance on horizontally oriented facial structure (i.e., the horizontal bias) can account for age differences in face identification accuracy. I examine the range over which orientation structure is integrated by varying bandwidth and whether the diagnostic structure is known or embedded within a non-informative context. Both younger and older adults showed a horizontal bias, and face identification accuracy for both orientation filtered and unfiltered faces was consistently lower in older than younger adults. In Experiment 1, an age difference in horizontal bias was observed only for faces presented in a non-informative context, whereas in Experiment 2, older observers' reduced horizontal bias did not depend on context. Horizontal bias and identification accuracy was positively correlated in older adults in both experiments, but only in Experiment 2 for younger adults. However, horizontal bias was unable to account fully for older adults' worse face identification.

Chapter 5 summarizes the findings of each data chapter, highlights my contributions to the field of visual neuroscience and aging, and suggests how my work can usefully be extended to other research avenues.

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Chapter 2

Classification images characterize age-related deficits in face discrimination

2.1 Preamble

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2.2 Abstract

Face perception is impaired in older adults, but the cause of this decline is not well understood. We examined this issue by measuring Classification Images (CIs) in a face discrimination task in younger and older adults. Faces were presented in static, white visual noise, and face contrast was varied with a staircase to maintain an accuracy rate of $\approx$71%. The noise fields were used to construct a CI using the method described by Nagai et al. (2013) and each observer's CI was cross-correlated with the visual template of a linear ideal discriminator to obtain an estimate of the absolute efficiency of visual processing. Face discrimination thresholds were lower in younger than older adults. Like Sekuler et al. (2004), we found that CIs from younger adults contained

structure near the eyes and brows, suggesting that those observers consistently relied on information conveyed by pixels in those regions of the stimulus. CIs obtained from older adults were noticeably different: CIs from only two older adults exhibited structure near the eye/brow regions, and CIs from the remaining older observers showed no obvious structure. Nevertheless, face discrimination thresholds in both groups were strongly and similarly correlated with the cross-correlation between the CI and the ideal template, suggesting that despite older observers' lack of consistent structure, the CI method is sensitive to between-subject differences in older observers' perceptual strategy.

2.3 Introduction

Older adults are impaired on a number of face perception tasks, such as eyewitness identification (Searcy et al., 1999), detecting manipulations to facial features (Slessor et al., 2012; Murray et al., 2010; Konar et al., 2013), identifying faces varying in expression (Ruffman et al., 2008) and/or viewpoint (Habak et al., 2008; Lee et al., 2011), and interpreting social cues (Halberstadt et al., 2011), yet the cause of these age-related declines is poorly understood. One possibility is that age differences in face perception are caused by older and younger adults relying on different sources of information, or different kinds of processing, to identify faces. For example, younger adults (Goffaux and Dakin, 2010; Pachai et al., 2013b) rely more heavily on horizontal than vertical structure to identify faces. But the reliance on horizontal structure is diminished with older observers (Obermeyer et al., 2012; Sekuler et al., 2014; Yu and Chung, 2011; Goffaux et al., 2015). The critical horizontal structure is concentrated around the eye/brow region (Duncan et al., 2017; Pachai et al., 2013a), a region that is particularly important for face identification (Sekuler et al., 2004; Pachai et al., 2013a; Gold et al., 2004; Gosselin and Schyns, 2001; Schyns et al., 2002) and some emotions (Smith et al., 2005; Duncan et al., 2017). Thus, age-related deficits in face processing may be due to the decreased efficiency with which older observers encode task-relevant information conveyed by the eye/brow region. This idea is consistent with behavioural studies showing older adults are less sensitive at discriminating changes in the spacing between the eyes than are younger adults (Chaby et al., 2011; Slessor et al., 2012).

Further support for an age-related deficit in processing information around the eyes is provided by several eye-tracking studies. Despite poorer recognition memory, older adults make more eye movement transitions between inner facial features (such as the eyes) than do younger adults (Firestone et al., 2007; Chan et al., 2011). Similarly, as faces become better learned, younger adults make fewer fixations to faces, and spend more time on critical regions (e.g., eyes) and relatively less time on uninformative regions (e.g., nose, mouth); however, older adults show no change in their distribution of fixations, and spend more time on uninformative regions such as the nose (Heisz and Ryan, 2011). Finally, older adults spend proportionately less time looking toward the upper- than lower-halves of upright angry, fearful, and sad faces compared to younger adults (Murphy and Isaacowitz, 2010; Wong et al., 2005), and this difference in gaze pattern is correlated with identification accuracy on at least some of these emotions (Murphy and Isaacowitz, 2010; Sullivan et al., 2007; Wong et al., 2005). However, these age differences in eye movements should be interpreted with caution because where one fixates may not provide a complete picture of the information observers use to perform a perceptual task.

Another potential explanation is that age-related declines in face processing are related to age differences in holistic processing, the extent to which faces are encoded and represented as a unified, integrated whole, rather than a simple linear summation of its component parts (see Maurer et al., 2002 for a review suggesting the importance of holistic processing for face perception; but see Sekuler et al., 2004; Gaspar et al., 2008; Konar et al., 2010 for an alternative view). Support for this hypothesis is equivocal: the results of some studies are consistent with impaired holistic processing in older adults (Murray et al., 2010; Schwarzer et al., 2010; Chaby et al., 2011; Slessor et al., 2012), whereas other results suggest that holistic processing does not decline (Boutet and Faubert, 2006) or perhaps becomes even more important for identifying faces and other objects, even as face discrimination performance declines (Dror et al., 2005; Adduri and Marotta, 2009; Pilz et al., 2010; Daniel and Bentin, 2012; Creighton et al., 2012; Konar et al., 2013).

One potential explanation for these equivocal findings is the presence of large individual differences or heterogeneity within the older adult population. Such heterogeneity would suggest that a full understanding of age-related differences in face processing would require examining how face encoding strategies differ across individuals. In the current paper, we begin to address this issue using response classification to derive classification images (CIs) of individual observers. Specifically, here we use the random sub-sampling variant of the CI method developed by Nagai et al. (2013), which allows for the estimation of stable classification images in far fewer trials than the traditional method (≈1500 vs ≈10,000; Sekuler et al., 2004; Gold et al., 2004), making it an ideal approach for studying special populations, such as older adults. To our knowledge, only one published paper (Éthier-Majcher et al., 2013) has used a related technique to explore judgements of facial trustworthiness in healthy older adults.

The response classification paradigm has several advantages over methods used in the studies described above: (1) it allows us to examine individual differences in face processing strategies in populations where substantial within-group variability might obscure between-group effects; (2) it does not require long duration stimuli; (3) it makes no *a priori* assumptions about regions of interest; thus it can reveal unexpected strategies not captured by other methods (e.g., feature displacement, composite faces, eye-tracking); and (4) it potentially reveals the relationship between an observer's response and perceptual strategy, to the extent that a given observer demonstrates a consistent relationship, while holding performance approximately constant across individuals. This last point is particularly relevant in cases where we expect significant differences to exist across individuals and groups.

In a typical response classification experiment, on each trial a unique external noise field is generated and added to one of two randomly chosen signals (e.g., Face A or Face B). The observer then must determine which stimulus was shown. For signals embedded in a high level of external noise, on some trials, by chance, the external noise will be distributed in such a way that Face A more closely resembles Face B, making the observer more likely to misclassify the stimulus as Face B. On other trials, the external noise may amplify characteristics of Face A that lead to a more likely Face A classification. After many trials, the contrast values of the noise fields are sorted into a 2 × 2 stimulus-response matrix, and the fields within each bin are averaged and combined to form a classification image (CI) using the equation:

$$\mathrm{CI} = (\overline{\mathrm{N_{AA}}} + \overline{\mathrm{N_{BA}}}) - (\overline{\mathrm{N_{AB}}} + \overline{\mathrm{N_{BB}}})$$

Where $\overline{\mathrm{N_{SR}}}$ denotes the pixelwise average of the noise fields for all trials in a given stimulus-response class (e.g., $\overline{\mathrm{N_{AB}}}$ represents the average of all noise fields for trials when the stimulus was Face A and the observer responded Face B). For a linear observer, the expected value of the CI is proportional to the observer's template (Murray et al., 2005). In other words, classification images can be conceptualized as "behavioural receptive fields" that provide a visual representation of how each region of the stimulus influences an individual observer's response (Gold et al., 2004). Using this approach, we can determine if older and younger adults use qualitatively similar sampling strategies (i.e., rely on the same information when discriminating faces), at the level of the individual observer, rather than at the level of age-groups; and examine the extent to which age differences in classification images are associated with age differences in face discrimination thresholds.

2.4 Methods

2.4.1 Observers

Ten younger (M = 23.3, SD = 3.56) and ten older (M = 71.7, SD = 6.95) Caucasian adults participated in this experiment either for cash ($10/hour) or partial course credit. Older adults were screened for visual pathologies with a vision and general health questionnaire. The Mini Mental State Examination (Folstein et al., 1975) and the Montreal Cognitive Assessment (Nasreddine et al., 2005) were used to screen for cognitive impairments in older adults; all MMSE and MoCA scores fell within the normal range. All participants had normal or corrected-to-normal Snellen visual acuity, and the groups also did not differ significantly on peak contrast sensitivity, as measured by the Pelli-Robson chart (Table 2.1). All but two participants (SEC and MVP) were unpracticed psychophysical observers with no prior exposure to the stimuli, and were naïve to the purpose of the experiment.

Table 2.1 – *Mean (SD)* age, near and far Snellen decimal acuity, Pelli-Robson contrast sensitivity, Mini-Mental State Exam (MMSE), and Montreal Cognitive Assessment (MoCA).

	N	Age	Near Acuity	Far Acuity	Pelli-Robson	MMSE	MoCA
Younger	10	23.3 (3.56)	1.3 (0.29)	1.3 (0.26)	1.97 (0.05)		
Older	10	71.7 (6.95)	0.9 (0.17)	1.0 (0.12)	1.88 (0.13)	28.9 (1.52)	26.9 (2.28)

2.4.2 Apparatus

Stimuli were generated on an Apple Macintosh G5 PowerPC (OS 10.5.8) using MATLAB (v 7.4.0) and the Psychophysics and Video toolboxes (Brainard, 1997; Pelli, 1997). Stimuli were presented on a NEC monitor (36 cm × 27 cm) with a resolution of 640 × 480 pixels and frame rate of 85 Hz. The average luminance of the display was 67 cd/m^2. The display was the only source of illumination in the testing room. Participants viewed the stimuli binocularly at a distance of 88 cm while seated in an adjustable chair. A chin rest was used to stabilize head position throughout the experiment.

2.4.3 Stimuli

The stimuli were two Caucasian male faces from the Gold et al. (1999) face set. These stimuli were chosen in order to be consistent with Nagai et al. (2013), who first used the random sub-sampling method in a special population. The stimuli were equated for amplitude spectrum and differed only in their phase spectrum (see Gold et al., 1999, for more details about the stimuli). Each face was centred in a 128 × 128 pixel array (4.41° × 4.41°), and the height and width of each face subtended a visual angle of 3.41° × 2.41°, respectively.

We used the random sub-sampling method first described by Nagai et al. (2013), which has been shown to yield similar face classification images as fully-sampled faces, but in a fraction of the trials. To create the sub-sampled stimuli, all pixels falling outside an elliptical mask surrounding the face were set to zero contrast. One pixel from each 2 × 2 pixel region of the face was randomly selected for presentation; the remaining three pixels in that region were set to zero contrast. The spatial location of the presented pixels was held constant within an observer and across sessions, but varied across observers. On each trial, a unique noise field was generated by randomly selecting contrast values from a Gaussian distribution with a mean of zero and a standard deviation of 0.3. Noise values more than two SD from the mean were resampled until all values were within range. The final image was created by adding this noise field to the face stimulus. Note that the noise fields contained non-zero values only at pixels that were shown in the sub-sampled faces. Figure 2.1 illustrates this stimulus generation process. In the experiment, contrast of the face stimulus was adjusted according to a single 2-down/1-up staircase maintaining response accuracy of approximately 71%.

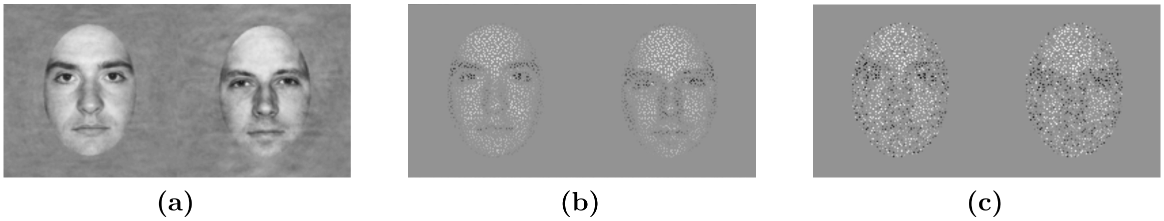

(a) **(b)** **(c)**

Figure 2.1 – Stimulus generation: a) fully-sampled, b) sub-sampled, c) sub-sampled plus noise.

2.4.4 Procedure

The McMaster University Research Ethics Board approved the experimental protocol, and written informed consent was obtained from all subjects prior to their participation.

The procedure was verbally explained to each participant, and task instructions were presented on the screen. Participants adapted to the average luminance of the display by fixating the centre of the computer screen for 60 s, and then completed two blocks of 20 practice trials to familiarize them with the task. In the first practice block, root mean square (RMS) face contrast was set to 0.3, and did not vary; in the second block, contrast was adjusted with a 2-down/1-up staircase maintaining response accuracy of approximately 71%.

Each trial began with a central fixation dot that was displayed for 1000 ms, followed by an individual face + noise stimulus for 506 ms, a blank screen for 200 ms, and then a response screen consisting of the two possible faces displayed at high contrast, without sub-sampling. Response screen stimuli were the same dimensions as target stimuli, centred 2.21° to the left and right of the centre of the display. Participants performed a face discrimination task by pressing one of two keys on a computer keyboard to indicate whether the stimulus was Face A (presented on the left) or Face B (presented on the right). Auditory feedback indicated whether the response was correct (high tone) or incorrect (low tone), and then the fixation dot appeared to indicate the beginning of the next trial. Unlimited response time was given, and participants were aware that the probability of either face appearing on a given trial was 50%.

Each session consisted of 1500 experimental trials, and participants were allowed a self-timed break every 100 trials. The two sessions usually were completed on consecutive days, with each session lasting approximately 90 minutes.

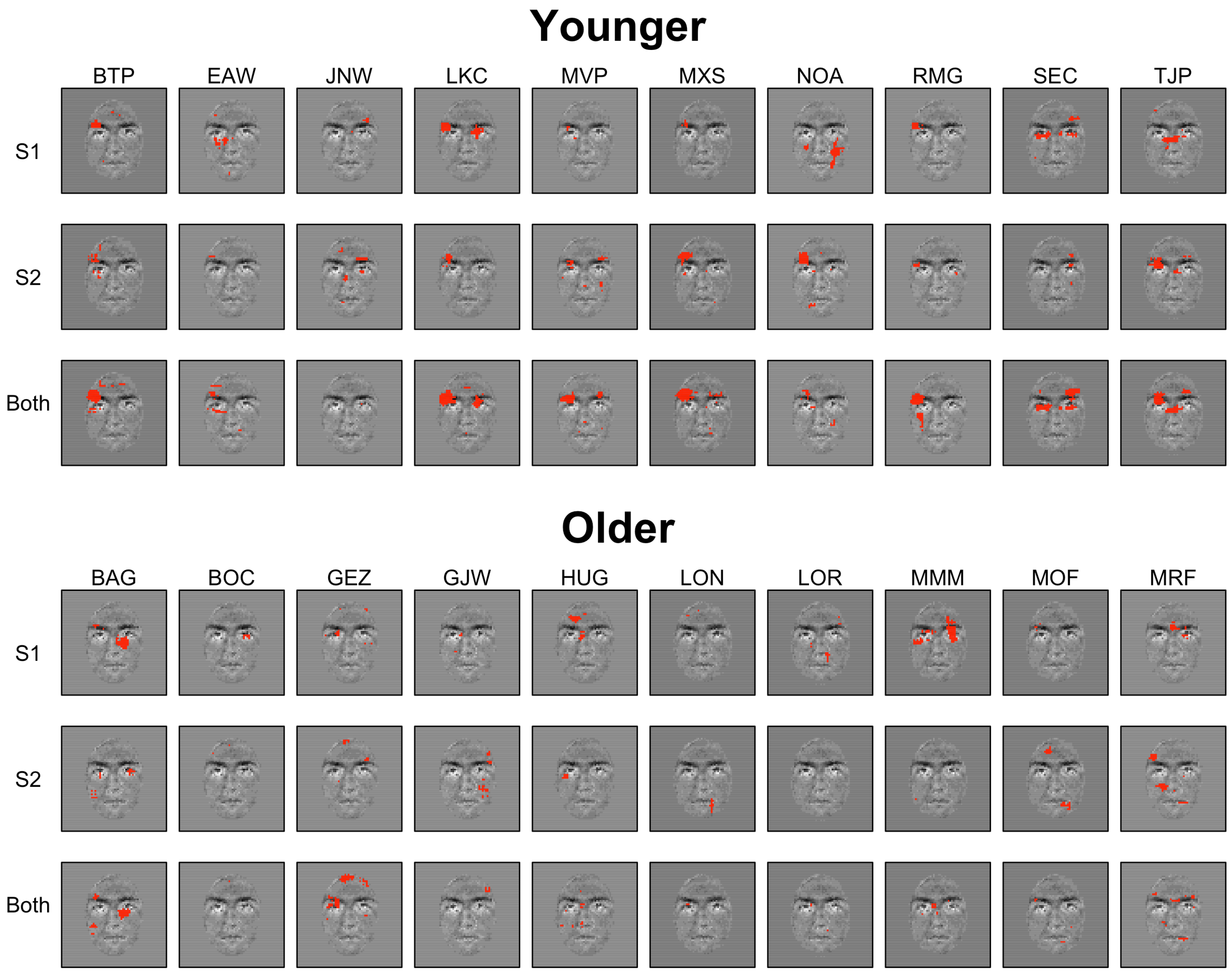


Figure 2.2 – Significant pixels ($p < .001$) in smoothed classification images for younger (top panel) and older (bottom panel) observers for each session alone (S1, S2) and after 2900 trials (both).

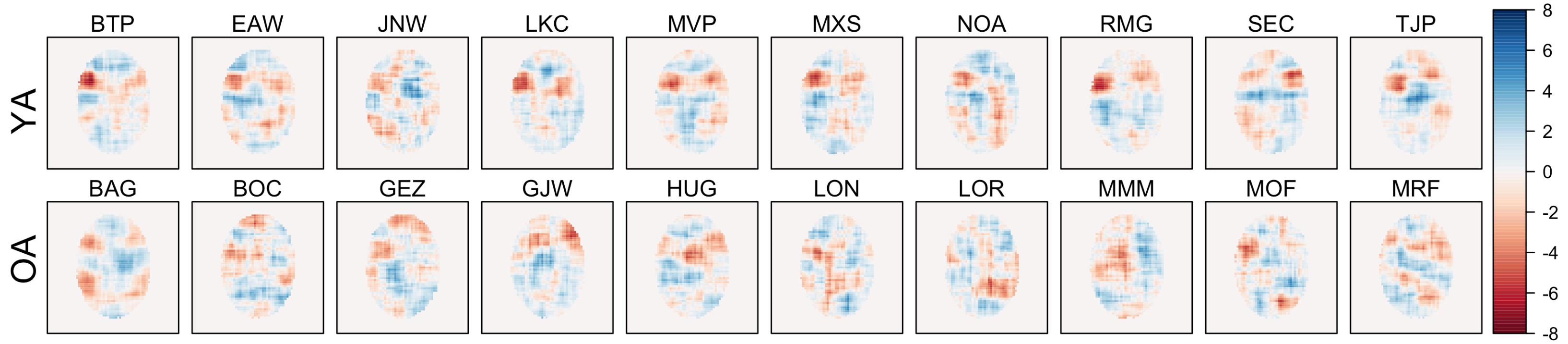


Figure 2.3 – Z-scored smoothed classification images for younger (YA, top panel) and older (OA, bottom panel) adults after 2900 trials. CIs were z-scored based on the individual distribution obtained from each observers' permutation test.

2.5 Results

As in Nagai et al. (2013), analyses were based only on sub-sampled pixels (i.e., pixels displayed to the participant). Classification images were estimated by sorting the contrast values of the noise fields presented on each trial into a stimulus-response matrix. The first 50 trials of each session were treated as practice trials and discarded, and classification images were estimated from the remaining 1450 trials per session for a total of 2900 trials. Thresholds were calculated as the average of the last 200 staircase reversals in each session. Analyses were performed in MATLAB (v 7.4.0) and R (R Core Team, 2016).

Further analyses quantified which pixels were correlated with observers' decisions. First, to increase the signal:noise ratio, smoothed classification images were created by convolving the compressed raw classification images with a 10×10 uniform convolution kernel. One consequence of this process is that pixel contrast is no longer independent, therefore calculating statistical significance levels using standard statistical tests is inappropriate. We therefore used the following permutation test to evaluate the null hypothesis that the values in the smoothed classification image could be produced by chance. The responses of each observer were shuffled randomly, and a series of 10 new, smoothed classification images were computed with the shuffled responses. Because there was no association between stimulus noise and the shuffled response, values in the smoothed classification images were used to estimate the distribution of CI pixel values that arise when the null hypothesis is true (Efron and Tibshirani, 1993). Statistical significance was determined by comparing the observed CI pixel values in an observer's filtered classification image with this null distribution. The Bonferroni correction for multiple comparisons tends to be too conservative, particularly when there are many tests that are not independent (Bland and Altman, 1995). Therefore, we chose instead to set the threshold for significance to $p < .001$ to facilitate comparisons with previous studies that used similar methods and stimuli.

Figure 2.2 shows the spatial location of significant pixels (red regions, $p < .001$) in the smoothed classification images of each observer in each age group for each individual session and combined across both sessions. Additionally, Figure 2.3 shows the z-scored version of younger (top) and older (bottom) observers' CIs for the combined sessions. By the end of session 2 (Figure 2.2), CIs from younger adults exhibit significant pixels mainly in the eye/brow regions, the primary exception being the CI from observer

JNW, which had few significant pixels. By contrast, even after 2900 trials, the CIs from most older adults had few significant pixels, and the small number of significant pixels were distributed more broadly across the face and to less informative regions, such as the forehead (GEZ, 54% of all significant pixels), nose (HUG, 60%), or mouth (MOF and MRF, 43% and 22% respectively). The CIs from two older observers (BAG & GEZ) did exhibit structure near the eye/brow regions (61% & 42%), but they also exhibited structure at less informative regions such as the cheek (BAG, 29%) and forehead (GEZ, 54%).

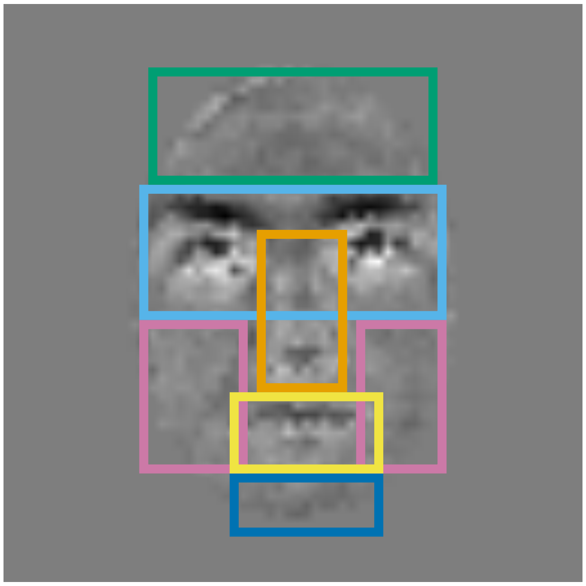
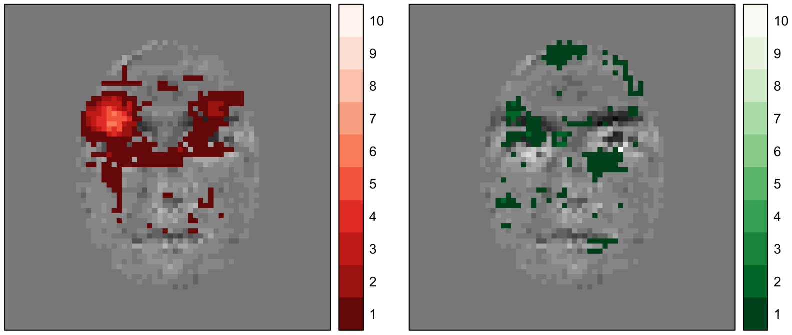
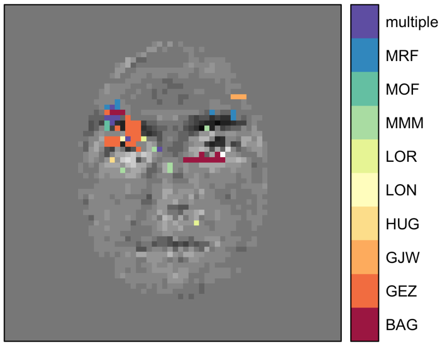


Figure 2.4 – Areas defined for the region of interest analysis. Anatomical features include the eyes, nose, mouth, forehead, cheeks, and chin. Note that significant pixels in the left and right cheek were summed for the analysis. Line width has been increased in the figure for the sake of visibility.

Figures 2.5a and 2.5b show the spatial distribution and density of significant pixels at the group level for the combined sessions. Note that these maps are only approximate in spatial location (a consequence of the sub-sampling being random for each subject) with the presented pixel in each 2 × 2 region treated as coming from the same position. Younger observers' decisions were nearly exclusively driven by the eye/brow region (Figure 2.5a), and showed considerable within-group consistency, with 7 of 10 observers relying on the left eye/brow. On the other hand, older observers demonstrated greater spatial variability and less consistency (Figure 2.5b), with at most 2 of 10 observers relying on the same pixel location. Figure 2.5c illustrates the overlap in classification images across age groups, by highlighting only pixels that were statistically significant in at least one younger and one older subject. This analysis suggests that, at the group level, classification images from younger and older observers did overlap to some degree, with observers in both groups relying on information conveyed by pixels near the eyes and brows. However, this overlap was driven nearly entirely by just two older observers, GEZ and BAG.



(a) younger **(b)** older



(c) overlap

Figure 2.5 – Spatial location and density of significant pixels, after 2900 trials, for younger (a) and older (b) observers, showing the number of observers relying on a given pixel location. Panel (c) illustrates the overlap between groups by highlighting only pixels that were statistically significant in the classification images from at least one younger and one older subject, colour coded by older participant. Instances where subject initials are not listed indicate either an absence of significant pixels, or significant pixels all fell within a region of overlap.

In younger adults, the distribution of significant pixels was relatively stable across sessions 1 and 2 (Figure 2.2). This stability is consistent with the results of Nagai

Table 2.2 – Normalized cross-correlation with ideal template (absolute efficiency), root mean squared (RMS) signal contrast threshold (threshold), and number of significant ($p < .001$) pixels in the smoothed classification image for younger and older observers, for each session alone (S1, S2) and combined (both). Cross-session consistency represents the cross-correlation of the spatial distribution of z-scores in the smoothed classification images between S1 and S2.

Observer	Cross-Correlation			Threshold			# pixels			Cross-session consistency
	S1	S2	Both	S1	S2	Both	S1	S2	Both	
Younger										
BTP	0.05	0.10	0.11	0.04	0.04	0.04	26	29	73	0.42
EAW	0.09	0.09	0.12	0.05	0.05	0.05	29	4	35	0.34
JNW	0.05	0.02	0.05	0.09	0.07	0.08	9	34	1	-0.40
LKC	0.04	0.07	0.08	0.08	0.09	0.08	62	21	97	0.32
MVP	0.13	0.09	0.16	0.03	0.03	0.03	6	32	53	0.15
MXS	0.06	0.05	0.08	0.06	0.06	0.06	8	42	79	0.24
NOA	0.03	0.08	0.08	0.05	0.05	0.05	62	51	23	-0.03
RMG	0.07	0.10	0.12	0.06	0.07	0.07	19	12	69	0.42
SEC	0.10	0.11	0.14	0.04	0.04	0.04	58	12	91	0.39
TJP	0.06	0.05	0.08	0.05	0.06	0.06	42	53	84	0.30
mean:	0.07	0.08	0.10	0.06	0.06	0.06	32.1	29.0	60.5	0.21
Older										
BAG	0.04	0.00	0.03	0.11	0.09	0.10	50	22	51	0.34
BOC	0.03	0.03	0.04	0.09	0.07	0.08	9	2	1	0.16
GEZ	0.00	0.06	0.04	0.17	0.14	0.16	15	15	74	0.20
GJW	0.05	0.07	0.09	0.07	0.07	0.07	5	29	7	-0.18
HUG	0.03	0.01	0.03	0.11	0.10	0.10	35	10	15	-0.03
LON	-0.02	0.05	0.02	0.27	0.19	0.23	3	13	2	-0.13
LOR	0.00	0.04	0.02	0.26	0.26	0.26	14	0	3	0.13
MMM	-0.01	0.04	0.02	0.17	0.14	0.16	91	1	12	-0.20
MOF	0.02	0.06	0.05	0.08	0.11	0.09	4	30	7	-0.21
MRF	0.05	0.01	0.04	0.10	0.13	0.11	24	43	27	-0.01
mean:	0.02	0.04	0.04	0.14	0.13	0.14	25.0	16.5	19.9	0.01

et al. (2013), who found that as few as 1450 trials were sufficient to obtain stable classification images in younger adults using the sub-sampling method employed here. On the other hand, older adults demonstrated less consistency across sessions. For example, in session 1 observer HUG used pixels in the forehead and nose region, but in session 2 HUG used a region near one eye; in session 1, the significant pixels for observer MOF were located in the left eye/brow region, but in session 2 they were located on the forehead and mouth; and observer MMM had significant pixels in the right and left eye/brow regions in session 1, but only one significant pixel in those regions in session 2, with a few additional significant pixels between the eyebrows by the end of 2900 trials.

Table 2.2 lists face discrimination threshold (RMS contrast) and the number of significant pixels in the smoothed classification image for each participant. Thresholds, averaged across sessions, were significantly higher in older observers than younger observers ($t(10.17) = 3.85$, $p = .002$, one-tailed). Additionally, consistent with our observations from Figure 2.2, classification images for older adults contained fewer significant pixels compared to younger adults, even after 2900 trials ($t(16.87) = 3.21$, $p = .003$, one-tailed). We performed a region of interest analysis by separately counting the number of significant pixels within the eyes, nose, mouth, forehead, cheeks, and chin (see Figure 2.4 for anatomically defined regions). For both groups, the majority of significant pixels were contained in the eye region ($M_Y = 0.82$, $M_O = 0.52$) relative to other facial features (nose: $M_Y = 0.05$, $M_O = 0.11$; mouth: $M_Y = 0.01$, $M_O = 0.05$; forehead: $M_Y = 0.20$, $M_O = 0.27$; cheeks: $M_Y = 0.06$, $M_O = 0.13$; chin: $M_Y = 0.00$, $M_O = 0.00$). As expected, younger adults relied more heavily on the eye region than did older adults ($t(12) = 3.94$, $p = .001$, one-tailed). No age difference was found for the nose, mouth, forehead, cheeks, or chin (all $ps > .21$). Pairwise t tests indicated that younger adults had more significant pixels in the eye compared to other regions (all $ps < .003$). Older observers tended to rely more on the eyes than the mouth and chin ($ps < .04$).

Table 2.2 also lists the cross-correlation of the observer's CI with the ideal template. If the classification image captures the important aspects of an observer's perceptual strategy, then we would expect absolute efficiency – as indexed by the cross-correlation between the CI and the ideal linear template – to be associated with an observer's threshold (Murray et al., 2005). Threshold is plotted as a function of the cross-correlation between the CI and ideal template in Figure 2.6. Threshold and cross-correlation values are significantly correlated overall ($r = -0.89$, $p < .001$, one-tailed) and in both younger ($r = -0.74$, $p = .007$, one-tailed) and older ($r = -0.73$, $p = .009$, one-tailed) participants. Additionally, averaged across sessions, older observers had significantly lower cross-correlations relative to younger observers ($t(14.48) = 4.75$, $p < .001$, one-tailed). We also estimated absolute efficiency for each observer by computing the squared ratio of human to ideal d' when face RMS contrast was set to the observer's threshold. This measure of absolute efficiency was significantly correlated with the measure based on the cross-correlation between CIs and the ideal template in each age group (younger: $r = 0.75$, $p = .006$; older: $r = 0.72$, $p = .009$, both one-tailed) and overall ($r = 0.89$, $p < .001$, one-tailed). Consistent with our previous analyses, older adults had lower observed absolute efficiency than younger adults ($t(10.3) = 4.02$, $p = .001$, one-tailed; $M_Y = 1.77\%$, $M_O = 0.39\%$). These results suggest that the classification images were sensitive to the group and individual differences that affected absolute efficiency in our task.

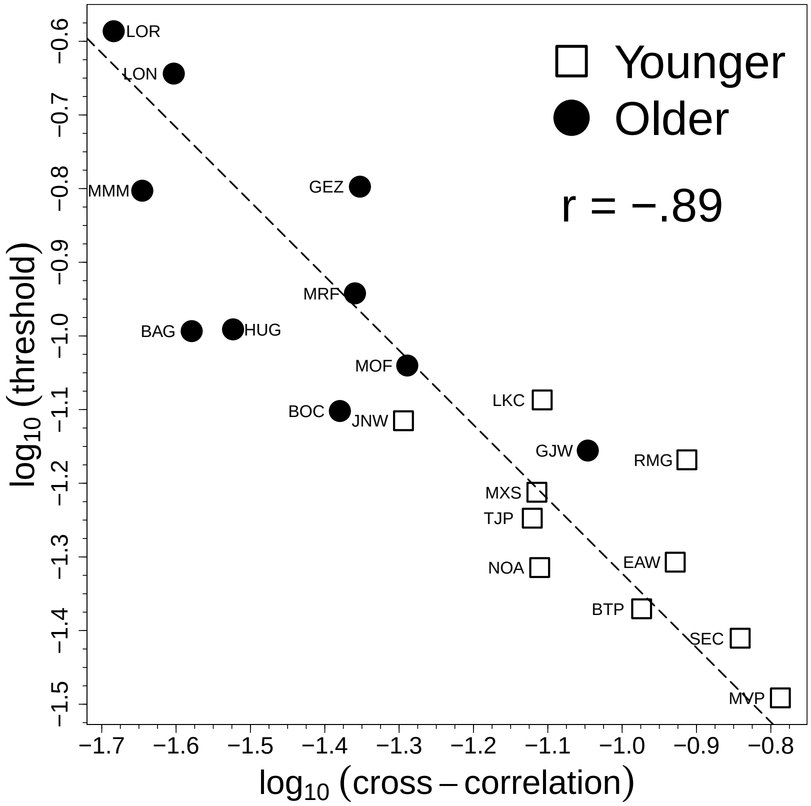


Figure 2.6 – Relationship between log-transformed root mean squared (RMS) contrast threshold and log-transformed normalized cross-correlation of the compressed raw classification image with the ideal template. Data combined across sessions. White squares and black circles represent younger and older observers, respectively. Dashed line represents regression line fit to data of both younger and older observers.

Finally, Table 2.2 contains a measure of cross-session consistency, which was calculated by cross-correlating the z-scores of the smoothed images obtained in sessions 1 and 2. Consistency was significantly lower in older adults compared to younger adults, ($t(16.74) = 2.04$, $p = .029$, one-tailed; see also Figure 2.2). In fact, older adults showed essentially *no* correlation at the group level ($t(9) = 0.11$, $p = .459$, one-tailed), and many showed a *negative* correlation between the sessions.

The data presented in Table 2.2 and Figure 2.6 suggest that between-subject variation was larger in the older group. For example, averaged across sessions, GJW had the highest cross-correlation and lowest threshold, yet the classification image for that observer had no apparent structure and few significant pixels. In addition, two older adults with relatively high thresholds (BAG & GEZ) had classification images that were qualitatively similar to those of younger adults, and showed the greatest number of significant pixels, but still had relatively low cross-correlations.

2.6 Discussion

The current study used the sub-sampling variant (Nagai et al., 2013) of the classification image technique to compare the spatial sampling strategies used by younger and older observers performing a face discrimination task. Consistent with previous findings, classification images (CIs) from younger adults exhibited significant spatial structure, which suggests that they consistently relied most heavily on the eye/brow region when making their decisions. By contrast, most older observers showed no clear structure in their classification images, and demonstrated greater within-group and cross-session variability. In addition, older adults were less sensitive (higher contrast thresholds), less efficient (lower cross-correlation with ideal template), and had higher cross-session variability (lower correlation between z-scored CIs) compared to younger adults.

What does the lack of consistent structure in older adults' classification images suggest? One possibility is that our method lacked a sufficient number of trials to detect older observers' strategy. Relatedly, it could be that our method does not adequately capture the strategy used by older observers. The structure in a classification image reflects all aspects of a linear observer's visual processing, but may fail to capture non-linear processes (Murray et al., 2005). If non-linearities play a more significant role in perceptual processing for older adults than for younger adults, one would expect to see less obvious structure in CIs from older observers. One way which non-linearities might manifest themselves is that older adults might be more reliant on holistic processing (Adduri and Marotta, 2009; Daniel and Bentin, 2012; Creighton et al., 2012; Konar et al., 2013), which might not be adequately represented by the structure within classification images. However, one aspect of our findings is inconsistent with this hypothesis. Specifically, we found that a measure of absolute efficiency derived from classification images was significantly correlated with discrimination thresholds in both age groups, suggesting that classification images were capturing important aspects of the perceptual strategies used by both younger and older adults.

The model we use here assumes performance is constrained by two factors intrinsic to the observer: (1) internal noise and (2) calculation efficiency (Pelli and Farell, 1999). The value of the cross-correlation of an observer's classification image with the ideal template, which is associated with absolute efficiency (Murray et al., 2005), is affected by internal noise *and* calculation efficiency. In other words, cross-correlations will be highest – and absolute efficiency will be highest – for observers with low internal noise and who use templates that are similar to the ideal template (i.e., have a high *calculation* efficiency). Therefore, higher levels of internal noise in older adults might account for the lack of observable structure in older adults' classification images, the low cross-correlations with the ideal template, and the increased inter-session variability among older observers. There is some neurophysiological evidence that visual cortical neurons exhibit greater noise in older animals (Schmolesky et al., 2000); however, other factors may contribute to an age difference in internal noise. For example, our results also are consistent with the possibility that older observers have greater variability in their response strategy across trials compared to younger adults, and this lack of consistency could result in reduced CI structure as well as higher estimates of internal noise (Burgess and Colborne, 1988) in the older group. Higher estimates of internal noise in older, relative to younger, observers have been found to contribute to age differences in motion detection (Bennett et al., 2007), direction identification (Bennett et al., 2007; Bogfjellmo et al., 2013), orientation discrimination (Betts et al., 2007; Allard et al., 2013), and detection of sine wave gratings at high (6-10 cpd) spatial frequencies (Pardhan, 2004). Thus, it is plausible that age differences in internal noise contributed to age differences in face discrimination thresholds found in the current study. It would therefore be fruitful for future studies to estimate the relative contributions of calculation efficiency and internal noise to older adults' reduced ability to discriminate faces. Another important consideration is how using the CI approach to age-differences in face perception might generalize to larger stimulus sets and/or different categories of faces (e.g., gender, age, race, etc.) than the two Caucasian male faces used here.

Nagai et al. (2013) found that classification images measured in a face discrimination task suggest that face processing strategies among ASD individuals fall into two distinct categories. Specifically, some ASD observers yielded classification images that were similar to those obtained from neurotypical observers, which suggests that they relied on information conveyed by pixels near the eyes and eyebrows. However, other ASD observers had classification images with atypical structure, suggesting that they based their responses on information conveyed by pixels on the forehead. Our results are similar, in the sense that they show that classification images in some, but not all, older adults are similar to those obtained in younger adults: two older observers showed a reliance on the eye/brow region similar to younger observers, whereas others relied on less informative areas such as the forehead or mouth. Our results also support the idea of greater within-group variability in older adults as we observed: (1) greater variability across sessions, and (2) greater absolute efficiency and lower contrast thresholds did not necessarily correspond with clearer structure, and spatial sampling strategies similar to younger observers did not necessarily correspond with higher absolute efficiency and lower contrast thresholds compared to older adults lacking structure.

An advantage of the classification image technique is that it makes no *a priori* assumptions about the spatial strategy employed by observers, and has a higher spatial resolution compared to other measures traditionally used in studying age-related changes in face perception. For example, studies of face perception that use eye-tracking often predefine regions of interest, such as the upper/lower halves of faces, or distinct facial features (most typically the eyes, nose, and mouth). By contrast, the response classification method examines performance at the level of a single pixel (or 2×2 clusters of pixels in the sub-sampling method), allowing us to observe older adults' reliance on regions such as the forehead, or cheek - areas typically assigned to an "other" category in eye-tracking studies. Furthermore, while it often is assumed that fixated positions represent regions critical to the observer performing the task, (i.e., information upon which they base their decisions and drives their performance), this may not always be the case. For example, Firestone et al. (2007) measured the gaze patterns of younger and older adults viewing faces who were subsequently given a surprise old/new memory recognition task. Despite increased sampling of face regions (more fixations and transitions between inner features such as the eyes), older adults demonstrated poorer recognition performance. The authors explain older adults' increased sampling as an attempt to use a compensatory strategy to overcome deficits in feature-binding (i.e., configural processing), yet their worse memory recognition suggests "such information was not used to make the recognition decision." Another study by Chan et al. (2011) further illustrates this point. In this study, younger and older adults were yoked to a gaze-contingent window tracking the patterns of either younger or older observers. Yoking older adults' eye-movements to those of younger observers did not increase performance on an old/new recognition task, and yoking younger adults' eye-movements to those of older observers did not decrease their performance. These studies thus lend support to the idea that the regions of the face that are sampled by older adults' eye movements may not correspond with the information actually driving older observers' decisions. The response classification technique, on the other hand, provides a direct measure of the relationship between information used and response accuracy.

In summary, the present study used a variant of the response classification technique to demonstrate both qualitative and quantitative differences in older and younger adults' performance on a face discrimination task. We replicated the finding that younger adults rely heavily on pixels in the eye/brow region when discriminating faces; however, the classification images from most older adults lacked obvious spatial structure. Nevertheless, we found that face discrimination thresholds in both age groups were strongly correlated with the similarity between the observed classification images and the ideal template, a result that suggests that classification images were sensitive to important aspects of face processing in both younger *and* older adults. Additionally, our results suggest that observer consistency may be lower, and between-subject variability may be higher, in older than younger adults.

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Chapter 3

Contribution of internal noise and calculation efficiency to older adults' face discrimination

3.1 Abstract

The efficiency with which observers discriminate faces declines with age. For example, using classification images (CIs) with sampled faces, Chapter 2 showed that older adults sampled diagnostic face information less efficiently compared to younger adults. Furthermore, many older adults showed no obvious structure in their CIs, suggesting increased internal noise may play a role in decreased performance. The current experiments assessed the relative contributions of internal noise and efficiency on age-related differences in face discrimination using the equivalent input noise and double-pass response consistency paradigms. Experiment 1 measured discrimination thresholds for faces embedded in several levels of static white noise: the resulting threshold-vs.-noise curves were used to estimate efficiency and equivalent input noise. Experiment 2 presented observers with two identical sequences of stimuli (i.e., faces embedded in static white noise) to measure the association between response accuracy and response consistency. The slope of the accuracy-vs.-consistency function provided an estimate of the internal:external (i/e) noise ratio for each observer. We found that both increased additive internal noise and decreased calculation efficiency contribute to age differences in face discrimination, but that i/e noise ratios were constant across

age groups. These results suggest that the age differences found in Chapter 2 reflect an age-related decline in efficiency of information use.

3.2 Introduction

The ability to discriminate and identify faces declines during normal healthy aging (Searcy et al., 1999; Habak et al., 2008; Grady et al., 2000; Grady, 2002; Owsley et al., 1981; Konar et al., 2013; Rousselet et al., 2009). What changes in the senescent visual system might account for this deficit in face identification? One way to address this question is to compare how human observers deviate from a theoretically optimal (i.e., ideal) observer designed to maximize performance. In the signal detection framework (Green and Swets, 1966), task performance is constrained by two factors intrinsic to the observer: the sum of any sources of internal noise present in the system, and the efficiency with which task-relevant stimulus information is utilized (often referred to as *sampling* or *calculation* efficiency). In human observers, higher internal noise and lower calculation efficiency lead to poorer performance relative to the ideal observer, and hence to lower *absolute efficiency*. Here, we examine the relative contributions of these two factors to older adults' face discrimination ability. Specifically, we assess whether age-related declines in face discrimination reflect increased internal noise, decreased calculation efficiency, or both an increase in internal noise *and* a decrease in calculation efficiency.

Chapter 2 used the classification image method to examine age-related changes in face discrimination. Classification images were obtained for younger and older adults who performed a face discrimination task for signals presented in a high level of external visual noise. As expected, face discrimination thresholds were significantly higher in older than younger adults. In addition, the classification images obtained in the two groups differed markedly: Consistent with previous studies of young adults (Sekuler et al., 2004; Nagai et al., 2013; Gold et al., 2004; Schyns et al., 2002), Chapter 2 found that classification images from younger adults possessed clear structure near the eyes and brows, but the classification images from most older adults exhibited no obvious spatial structure. Nevertheless, in both age groups the cross-correlation between the classification images and ideal linear template was correlated significantly with face discrimination thresholds in both age groups, which suggests that the spatial structure (or lack thereof) in the classification images was sensitive to age-related changes in performance.

The results of Chapter 2 are consistent with the idea that older adults do not consistently sample the most informative regions of a stimulus, which would mean that they have lower calculation efficiency compared to younger adults. For example, some older adults relied on less informative face regions such as the forehead or mouth. However, age differences in the spatial structure of the CIs may not be due entirely to changes in calculation efficiency, because the value of the cross-correlation between a classification image and ideal linear template is affected by *both* the observer's internal noise and calculation efficiency (Murray et al., 2005). Therefore, age differences reported in Chapter 2 in the spatial structure in observers' CIs, as indexed by the lower cross-correlations between the CIs and the ideal linear template, also are consistent with the idea that face discrimination in older adults is constrained by higher internal noise relative to younger adults. The current experiment uses two different psychophysical procedures – external noise masking and response consistency – to measure age-related changes in calculation efficiency and internal noise.

3.2.1 External noise-masking

Here, we interpret our data in the context of an early-noise model (Pelli and Farell, 1999) of a human observer's decision process. First, a constant, contrast-independent internal noise is added to the transduced stimulus. Next, a contrast-independent computation is performed that reduces the input to a single decision variable. In this framework, the performance of an observer is limited by the variance of the noise and degree to which the calculation extracts task-relevant information from the stimulus, which often is referred to as the efficiency of the calculation. The external noise paradigm estimates these two parameters by measuring thresholds both with and without visual external white noise added to the signal. When expressed as squared RMS contrast, c^2_{RMS}, face discrimination thresholds vary linearly with external noise variance, σ^2_E (Gold et al., 2004; Gaspar et al., 2008). Thus, in this model, the noise-masking function for faces can be fully characterized by the equation:

$$c^2_{RMS} = k(\sigma^2_E + \sigma^2_I) \tag{3.1}$$

where σ^2_I is the negative of the x-intercept and k is the slope of the line. Note that the noise-masking function is curved when plotted in log-log coordinates, and σ^2_I and

k respectively correspond to the knee and overall height of the curve (see Figure 3.1). The parameter σ_I^2, which is referred to as equivalent input noise, is defined as the external noise variance that is required to double an observer's zero-noise threshold. In the early-noise model described by Pelli and Farell (1999), σ_I^2 is an estimate of additive internal noise. The slope parameter, k, represents how quickly thresholds increase with increasing external noise variance, and $1/k$ is proportional to a value that has been referred to as sampling efficiency, calculation efficiency, and high-noise efficiency (Pelli and Farell, 1999).

Often, the human observer's value of k is compared to that of an ideal observer to derive an estimate of absolute efficiency, which provides a more direct estimate of the proportion of information actually used by a human observer (Geisler, 1989; Green and Swets, 1966). The ideal decision rule for the tasks used in the current experiments is to cross-correlate the stimulus with matched linear templates (one for each possible face) and to select the face corresponding to the template that yields the biggest response. Tjan et al. (1995) showed that an ideal observer's threshold in this type of task, expressed as squared RMS contrast, is a linear function of the external noise variance:

$$c_{ideal}^2 = k_{ideal} \times \sigma_E^2 \tag{3.2}$$

where the slope of the function, k_{ideal}, depends on the similarity among the various stimuli (i.e., how difficult the task is). High-noise efficiency, η^*, is defined as:

$$\eta^* = \frac{c_{ideal}^2}{c_{human}^2} = \frac{k_{ideal} \times \sigma_E^2}{k_{human} \times (\sigma_I^2 + \sigma_E^2)}. \tag{3.3}$$

When $\sigma_E^2 \gg \sigma_I^2$, high-noise efficiency is approximately equal to absolute efficiency, η, which is given by the equation:

$$\eta \approx \frac{k_{ideal} \times \sigma_E^2}{k_{human} \times \sigma_E^2} = \frac{k_{ideal}}{k_{human}}. \tag{3.4}$$

Figure 3.1 shows several hypothetical noise-masking curves, plotted in log-log coordinates, that illustrate the independent effects of changes in σ_I^2 and k. First, imagine a scenario where age-related increases in contrast thresholds are due entirely to an increase in σ_I^2. For example, older adults could have a higher baseline rate of spontaneous neuronal firing, causing thresholds to increase by a constant factor across noise levels. When plotted on log axes, increasing equivalent input noise by a constant

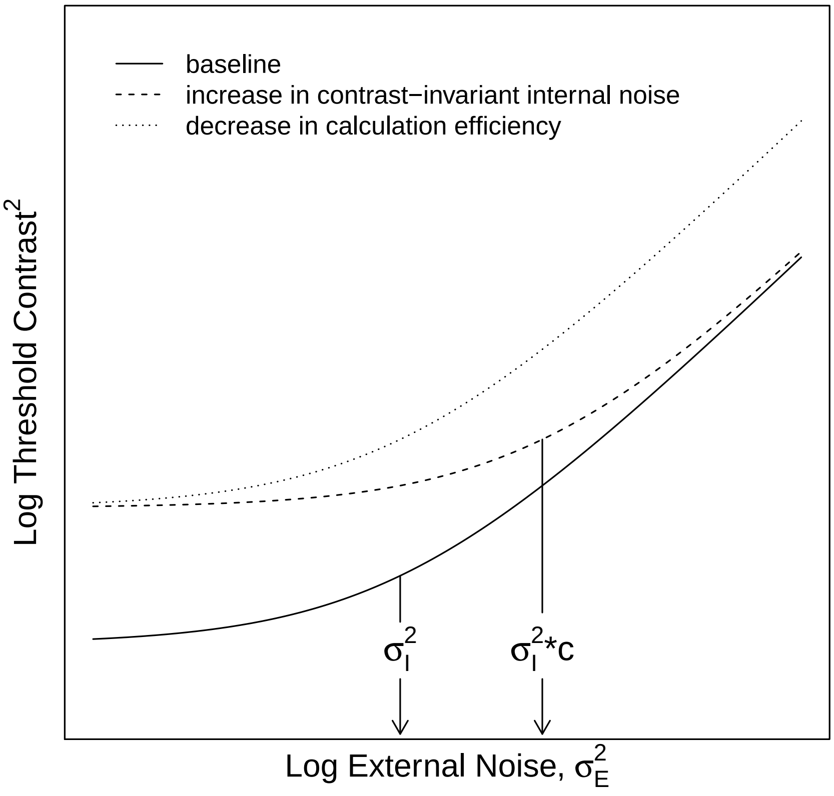

Figure 3.1 – Hypothetical noise-masking functions illustrating the differential effects of changes in the parameters of Equation 3.1. Log contrast threshold, c^2_{RMS}, is plotted as a function of log external noise variance, σ_E^2. The dotted line represents a decrease in calculation efficiency (using k as an index) by a constant factor c relative to the solid line. The dashed line represents an increase in contrast-independent internal noise by a constant factor c relative to the solid line.

factor has a larger effect on thresholds at lower than higher external noise levels, thus shifting the kink point, or knee, of the noise-masking function horizontally along the x-axis to the right. If age-related declines in face discrimination are attributable to increased equivalent input noise alone, age differences should be most pronounced at lower levels of external noise, where σ_I^2 is the dominant factor constraining performance, and become less pronounced as external noise increases. In this scenario, the noise-masking functions for younger and older adults would look like the solid and dashed lines, respectively, in Figure 3.1. Some neurophysiological research in senescent non-human animals suggest visual cortical neurons exhibit greater noise (Schmolesky et al., 2000). In human observers, age-related increases in internal noise have been reported for motion detection (Bennett et al., 2007), direction discrimination (Bennett et al., 2007; Bogfjellmo et al., 2013), orientation discrimination (Betts et al., 2007) and detection of of sine wave gratings at high (10 cpd) spatial frequencies (Pardhan, 2004). Higher level mechanisms at the level of the decision process, such as variability in response strategy across trials (Burgess and Colborne, 1988; Burgess, 1990), could also contribute to increased estimates of equivalent input noise.

Alternatively, higher face discrimination thresholds in older adults could entirely be due to an increase in the slope, k, of the noise-masking function (dotted line in Figure 3.1). When plotted in log-log coordinates, an increase in k, which corresponds to a decrease in calculation efficiency, causes the noise-masking curve to shift upwards by an equal amount at all external noise levels. Such a result could arise from sub-optimal sampling of informative face regions. In many tasks, including the one used here, the optimal strategy is to use a linear filter, or template, that is matched to the spatial and temporal characteristics of the stimulus. An observer computes a cross-correlation between the stimulus and each possible signal, and selects the response that yields the highest cross-correlation. If older observers apply linear filters that are less similar to the ideal compared to younger observers, this will result in higher values of k and hence decreased efficiency (Figure 3.1). Bennett et al. (1999) found such a result for detecting sine wave gratings embedded in noise: older observers were less efficient than younger observers, but no age-difference in equivalent input noise was found. The results of Chapter 2 provide evidence that older observers may use filters that are less well matched to the stimulus, relative to younger observers. For example, the eye/brow region carries important information about face identity, and classification image studies find that younger adults rely on this region heavily (Creighton et al., 2019; Sekuler et al., 2004; Nagai et al., 2013; Gold et al., 2004). On the other hand, several older adults from Chapter 2 made use of relatively less informative regions such as the mouth or forehead, suggesting their template is not as well matched to the stimulus compared to their younger counterparts.

3.2.2 Response consistency

As previously mentioned, absolute efficiency is affected by internal noise *and* calculation efficiency. The early-noise model described in the previous section assumes that all internal noise is a constant, additive noise (i.e., parameter σ_I^2 in Eq. 3.1), and therefore that vertical shifts of the threshold-vs.-noise curve in Figure 3.1 are due to changes in efficiency (i.e., changes in parameter k in Eq. 3.1). However, there may be other sources of internal noise that vary with stimulus contrast (Burgess and Colborne, 1988; Tolhurst et al., 1983). Such contrast-dependent, or multiplicative, internal noise also affect the slope of the noise-masking function. This presents a difficulty in interpreting k as a pure measure of the efficiency of a contrast-invariant calculation. Fortunately, the double-pass response consistency method allows us to measure contrast-dependent internal noise by observing how percent correct and percent agreement co-vary for two identical stimulus sequences (Burgess and Colborne, 1988; Green, 1964; Spiegel and Green, 1981). On the first pass, the value of each pixel in the stimulus-plus-noise array, as well as the observer's response, are recorded for each trial. In the second pass, the entire process is repeated with an *identical* sequence of stimuli, and a function relating response accuracy and response consistency is estimated using the data from both passes (Figure 3.2). The degree of response consistency at each level of response accuracy, and therefore the slope of the response consistency function, is determined by the ratio of the internal and external noise standard deviations at the level of the decision variable (Green, 1964; Burgess and Colborne, 1988; Spiegel and Green, 1981). For example, an observer with zero internal noise will respond identically, whether correct or incorrect, to corresponding trials in this second pass. That is, response consistency will be 100%, and the curve will fall along the right side of the plot in Figure 3.2. Observers with a high internal-to-external noise ratio will have relatively shallower slopes, and look like the hypothetical data shown in the white squares in Figure 3.2, whereas observers with a relatively lower internal-to-external noise ratio will look more like the data depicted with the black circles. Both additive and multiplicative internal noise can affect task performance; however, once the external noise exceeds 2-3 times an observer's detection threshold, the contribution of additive internal noise is negligible, and the dominant source of internal noise will be contrast-dependent (Burgess and Colborne, 1988). If older adults show worse face discrimination because they have increased multiplicative internal noise, then they will have a higher internal-to-external noise ratio, lower response consistency, and shallower response consistency functions compared to younger adults. If, on the other hand, the response consistency functions of younger and older adults do not differ, then higher values of k in older adults observed in the equivalent input noise experiment and lower absolute efficiency in Chapter 2 are attributable entirely to decreases in sampling efficiency.

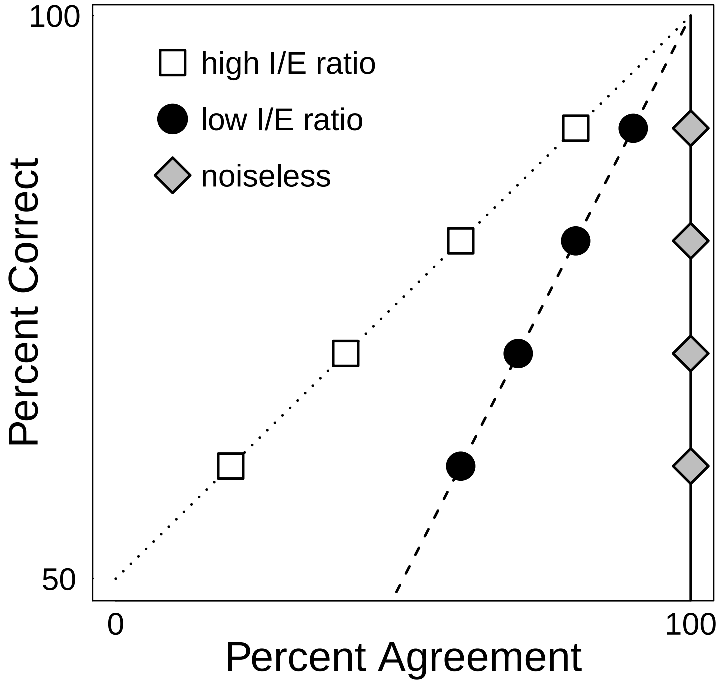

Figure 3.2 – Response consistency curves for three sets of hypothetical data. Percent correct is plotted against the percentage of trials on which an observer gives the same response (i.e., "agrees") on two identical trials. Each point represents data for a single target contrast. The diamonds illustrate data for a noiseless observer with perfect response consistency. The squares and circles illustrate results for observers with internal:external noise ratios that are high and low, respectively. If internal noise increases with age, then the slope of response consistency functions should be shallower for older adults relative to younger adults.

3.3 Experiment 1: External noise-masking

3.3.1 Methods

3.3.1.1 Participants

Sixteen younger (M = 24.7, SD = 5.4) and eighteen older (M = 71.0, SD = 6.1) Caucasian adults participated in this experiment. All participants had normal or corrected-to-normal Snellen visual acuity. Older adults were screened for visual pathologies with a vision and general health questionnaire. Cognitive impairments were assessed with the Mini Mental State Examination (Folstein et al., 1975) and Montreal Cognitive Assessment (Nasreddine et al., 2005); all scores fell within the normal range. With the exception of one younger adult (the first author), all participants were naïve to the purpose of the experiment. The first author was a highly practiced psychophysical observer. Two younger and eight older observers previously participated in the classification image experiment (Chapter 2), and thus had prior experience with the stimuli. The remaining observers had no prior exposure to the stimuli in this experiment. All participants were paid ($10/hour) or received partial course credit for their participation, and written informed consent was obtained from all subjects prior to their participation. The experimental protocols were approved by the McMaster University Research Ethics Board.

3.3.1.2 Apparatus

Stimuli were generated on an Apple Macintosh G5 PowerPC using MATLAB and the Psychophysics and Video Toolboxes (Brainard and Vision, 1997; Pelli, 1997). Stimuli were presented on a 19” Sony Trinitron display (40 cm × 30 cm) with 640 × 480 resolution and frame rate of 120 Hz. Average luminance was 66.6 cd/m^2. The display was the only source of illumination in the testing room. Participants viewed the stimuli binocularly from a distance of 104 cm while seated in an adjustable chair. A chin rest was used to stabilize head position throughout the experiment.

3.3.1.3 Stimuli

The stimuli were the same as those used in Chapter 2. Face stimuli were frontal views of two Caucasian male faces from the Gold et al. (1999b) face set. The faces had neutral expressions and had no piercings, facial hair, or glasses. The faces were cropped by an oval window and centred in a 128 × 128 pixel (4.41° × 4.41°) array, which subtended a visual angle of 3.41° × 2.41° height and width, respectively. Additional details about the stimuli are provided by Gold et al..

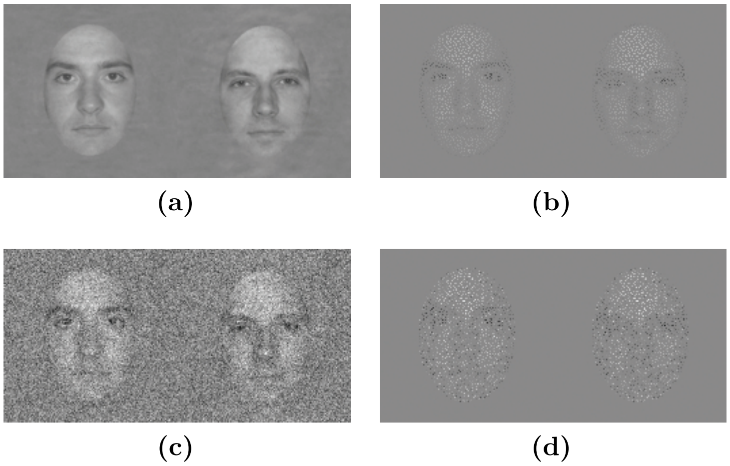

Figure 3.3 – Stimulus generation: a) full-face, b) sampled-face, c) full-face plus noise, d) sampled-face plus noise.

On each trial, the face stimulus was embedded in a unique noise field that was generated by randomly sampling contrast values from a zero-mean Gaussian distribution. The noise variance, σ_E^2, was 0, 0.001, 0.009, 0.09, or 0.16 (randomly intermixed across trials). To ensure all noise contrast values were in the displayable range of the monitor, noise values that were more than two standard deviations (SD) from the mean were replaced by resampling the noise distribution until all values were within ±2 SD.

As in the classification image experiment of Chapter 2, in some conditions the faces were modified using the random sampling method described by Nagai et al. (2013). To create the sampled stimuli, we created a sampling matrix by randomly selecting one pixel from each 2 × 2 pixel region in the image matrix for presentation and setting the value of that pixel to one and the remaining three pixels in that region to zero. The spatial locations of the presented pixels were held constant within an observer and across experiments, but varied across observers. Next, all pixels falling outside the elliptical mask that was used to crop the face were set to zero contrast. After adjusting full-face root-mean squared (RMS) contrast and adding the appropriate level of σ_E^2, the face image was multiplied by the elliptical mask and the sampling matrix to create the sampled stimulus. Figure 3.3 illustrates the stimulus generation process.

One consequence of the sampling operation being applied *after* adjusting the face contrast is that contrast of the final stimulus was lower in the sampled-face condition relative to the full-face (i.e., unsampled) condition. This difference in contrast is readily apparent from a comparison of the two conditions in zero noise (i.e., panels a and b in Figure 3.3). The sampling operation has the same effect on the contrast variance of the noise. Our estimates of thresholds and noise masking functions took into account these quantitative differences between the sampled-face and full-face conditions. In other words, our analyses were based on the actual face and noise RMS contrasts presented to the observer rather than the nominal values that were used to create the stimuli.

3.3.1.4 Procedure

At the start of each block of trials, participants adapted to the average luminance by fixating the centre of the display for 30 s. Each trial began with a central fixation dot that was displayed for 1 s, followed by a face + noise stimulus for 500 ms, a blank screen for 200 ms, and then a response screen consisting of the two possible faces displayed at high contrast without noise or sampling. Response screen stimuli were the same dimensions as target stimuli, centred 2.21° to the left and right of the centre of the display. Participants performed a face discrimination task by pressing one of two keys on a computer keyboard to indicate whether the stimulus was Face A (presented on the left) or Face B (presented on the right). Auditory feedback indicated whether the response was correct (high tone) or incorrect (low tone), and then the fixation dot appeared to indicate the beginning of the next trial. Unlimited response time was given, and participants were aware that the probability of either face appearing on a given trial was 50%. No practice trials were given; however, the experimenter remained in the room for the first several trials to ensure participants understood the task and had no questions.

The levels of external noise were intermixed randomly within each block. Discrimination thresholds were measured for each level of noise by adjusting RMS face contrast across trials using a 2-down/1-up staircase. A block of trials ended when every staircase had at least 12 reversals. On average, each block of trials lasted approximately 15 minutes and consisted of 200-250 trials. Participants were allowed a self-timed break every 100 trials.

Observers participated in two sessions that occurred at similar times on consecutive days. Each session contained two blocks of trials using full faces and two blocks of trials using sampled faces. The order of stimulus type (i.e., full vs. sampled) was counterbalanced across participants and days.

3.3.1.5 Ideal Observer

Monte Carlo simulations were used to calculate ideal observer thresholds. At each non-zero level of external noise, the method of constant stimuli was used to simulate 5000 trials at 15 levels of stimulus contrast that covered a two log unit range centred on an initial threshold guess. A Weibull function was fit to these data, and threshold was defined as the stimulus contrast yielding 71% correct. Equation 3.2 was fit to ideal thresholds, and Equation 3.4 was used to estimate absolute efficiency.

3.3.2 Results

Statistical analyses were performed in R (R Core Team, 2019). F tests conducted on within-subjects factors used degrees-of-freedom and p values that were adjusted with the Huynh-Feldt correction for departure from sphericity (Maxwell et al., 2017). Two-sample t tests used degrees-of-freedom that were adjusted using the Welch-Satterthwaite correction for unequal variances (Welch, 1947). Unless noted otherwise, two-tailed tests are reported. Cohen's d and partial eta-squared (η_p^2) are reported as measures of effect size and association strength, respectively. Means and standard deviations are reported in the units used for the corresponding statistical analysis.

3.3.2.1 Thresholds & Noise-Masking Functions

Threshold was defined as the average of the last four staircase reversals. There were four estimates of threshold in each condition which were averaged to provide a single estimate of threshold for each level of noise and stimulus type. Examination of the individual staircases indicated one older observer was unable to perform the task with either type of stimuli, even in the zero noise condition. A second older observer was unable to perform the task at high external noise levels for the sampled face condition. These two subjects were removed from all subsequent analyses. Equation 3.1 was fit to thresholds measured in each level of external noise to derive estimates of k and σ_I^2 for full and sampled faces for each participant with the constraint that $\sigma_I^2 > 0$.

Our derivation of the noise-masking parameters, k, and σ_I^2 assumes that the external noise had a significant impact on threshold. A casual examination of Figure 3.4 indicates that this was the case for full faces and sampled faces in both age groups. A second assumption is that thresholds are well fit by Equation 3.1. Others have shown this is true for younger adults performing identification and discrimination tasks with full faces (Gold et al., 2004; Gaspar et al., 2008); however we know of no previous work showing thresholds obtained with sampled stimuli conform to this model. Furthermore, it is unknown whether older adults' face discrimination thresholds for either type of stimulus are well fit by Equation 3.1. To test these assumptions, we first assessed the linear fit of the model to the average thresholds in both age groups. As shown in Figure 3.4, Equation 3.1 provided good fits to the average data from younger and older adults (young full: $R^2 = .997$; young sampled: $R^2 = .996$; old full: $R^2 = .999$; old sampled: $R^2 = .979$) We also assessed the fits for individual observers. A total of 64 (2 (full & sampled faces) $\times$ 32 participants) fits were performed. Of these, 8 (three younger, five older) observers showed poor fits ($p \geq .05$) to the noise-masking function for at least one stimulus type ($\approx$ 13% of the fits). Averaging the adjusted R^2 values across observers also indicated these data were well fit by Equation 3.1 (young full: $R^2 = .90$; young sampled: $R^2 = .86$; old full: $R^2 = .88$; old sampled: $R^2 = .75$). Hence, Equation 3.1 provided good fits to the data, and therefore it is reasonable to use Equation 3.1 in the estimation of equivalent input noise and efficiency for the stimuli and observers in the current experiment.

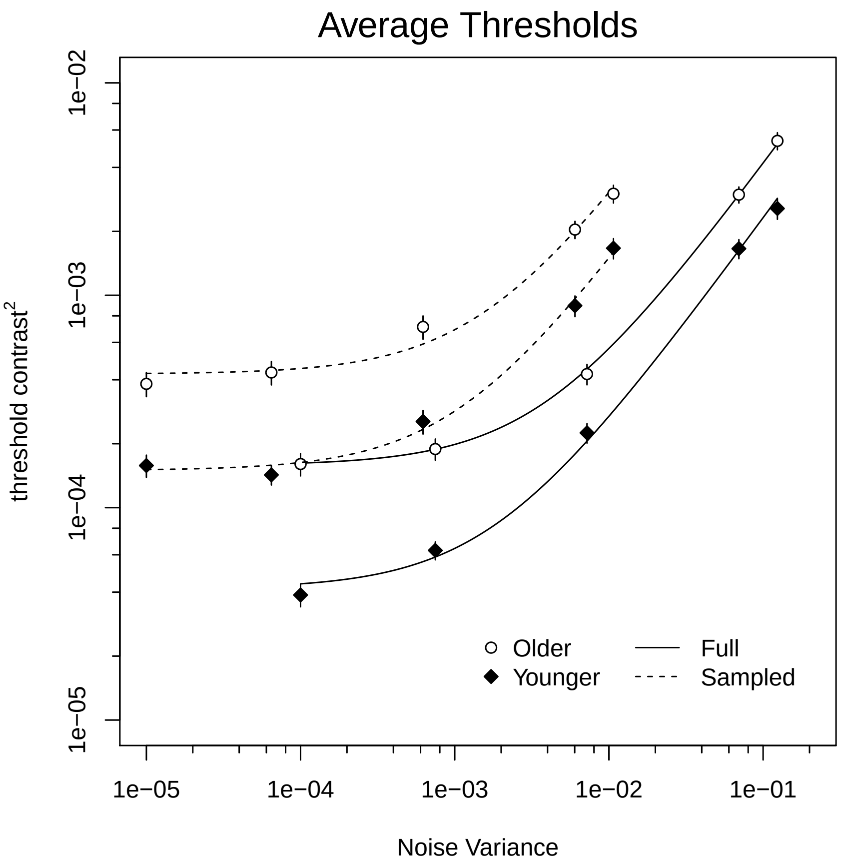

Figure 3.4 – Noise-masking curves for full (solid lines) and sampled (dashed lines) stimuli, for younger (filled diamonds) and older (open circles) observers. The noise variances have been adjusted for stimulus sampling in the sampled face condition. Curves were fit to the average data for each age group and stimulus condition using Equation 3.1. Error bars represent ±1 SEM.

3.3.2.2 Face discrimination thresholds

Discrimination thresholds for full and sampled faces are plotted as a function of external noise for both age groups in Figure 3.4. In both age groups, thresholds generally increased with increasing levels of external noise. Across comparable levels of external noise, thresholds in the full-face condition were lower than thresholds in the sampled-face condition. In all conditions, thresholds were higher in older than younger adults, and the age difference was larger at low levels of external noise.

Although contrast thresholds were calculated, it is not possible to make a quantitative comparison between the two stimulus types at each level of external noise for this experiment because sampling reduced external noise contrast variance by 7% relative to the unsampled noise. Therefore, we chose to perform separate 2 (Age Group) × 5 (Noise Level) on log-transformed thresholds at each level of Stimulus (Full vs. Sampled). In both cases, the main effects of Age (full: $F(1, 30) = 8.02$, $\eta_p^2 = .21$, $p = 0.008$; sampled: $F(1, 30) = 7.04$, $\eta_p^2 = .19$, $p = 0.01$) and Noise (full: $F(3.67, 109.98) = 464.5$, $\eta_p^2 = .94$, $p < 0.001$; sampled: $F(3.57, 107.05) = 114.38$, $\eta_p^2 = .79$, $p < 0.001$) were significant. The Age × Noise interaction was significant for full faces ($F(3.67, 109.98) = 4.82$, $\eta_p^2 = .14$, $p = 0.002$) but not sampled faces ($F(3.57, 107.05) = 1.13$, $\eta_p^2 = .04$, $p = 0.35$).

3.3.2.3 Noise-masking functions

The smooth curves in Figure 3.4 represent the noise-masking functions (Eq. 3.1) that were fit to the average data from younger and older observers. Recall that varying equivalent input noise causes the knee of the noise-masking function to shift horizontally in log-log coordinates, whereas changes in efficiency alter the overall height of the curves (Figure 3.1). Examination of the noise-masking curves in Figure 3.4 suggests that, for full faces (solid lines), older adults are less efficient than younger adults - indicated by the fact that the overall height of their curves is higher. Further, the knee of older observers' curve for full faces is shifted to the right relative to younger observers, suggesting an age-related increase in equivalent input noise. The curves for sampled faces (dashed lines) similarly suggest older adults have lower efficiency and higher equivalent input noise relative to younger adults, although the latter effect is less marked compared to full faces. This result is consistent with the hypothesis that age-differences in additive internal noise potentially might be smaller for faces using the sampling method.

The distributions of the best-fitting parameters for Eq. 3.1 are illustrated with box plots in Figure 3.5. Compared to younger observers, older observers exhibited higher equivalent input noise (σ_I^2) and lower calculation ($1/k$) and absolute (η) efficiency for both full and sampled faces. In both age groups, the values of $1/k$ were significantly higher with full faces than sampled faces; however, values of η, which take into account the available stimulus information, were *lower* with full faces.

These observations were evaluated quantitatively by performing separate 2 (Age Group) × 2 (Stimulus) ANOVAs on log-transformed equivalent input noise and absolute efficiency derived from the noise-masking functions for each participant. For equivalent input noise, the main effects of Age ($F(1, 30) = 10.66$, $\eta_p^2 = .26$, $p = 0.003$) and Stimulus ($F(1, 30) = 20.66$, $\eta_p^2 = .41$, $p < .0001$) were significant, but there was no evidence of an Age × Stimulus interaction ($F(1, 30) = 1.66$, $\eta_p^2 = .05$, $p = 0.207$).

Although older observers were numerically less efficient compared to younger observers ($M_Y = 0.94\%$, $M_O = 0.45\%$), the ANOVA on absolute efficiency found that the main effect of Age was not statistically significant ($F(1, 30) = 3.67$, $\eta_p^2 = .11$, $p = 0.065$). However, our *a priori* hypothesis about the effect of Age on efficiency was directional – we expected efficiency would be *lower* in older adults – and therefore a one-tailed test is appropriate. A one-tailed test shows the effect of Age is significant ($p = 0.033$). The main effect of Stimulus was significant ($F(1, 30) = 154.40$, $\eta_p^2 = .84$, $p < 0.001$) and reflected the fact that absolute efficiency was higher for sampled faces than full faces. Finally, the Age × Stimulus interaction was not significant ($F(1, 30) = 0.40$, $\eta_p^2 = .01$, $p = 0.534$).

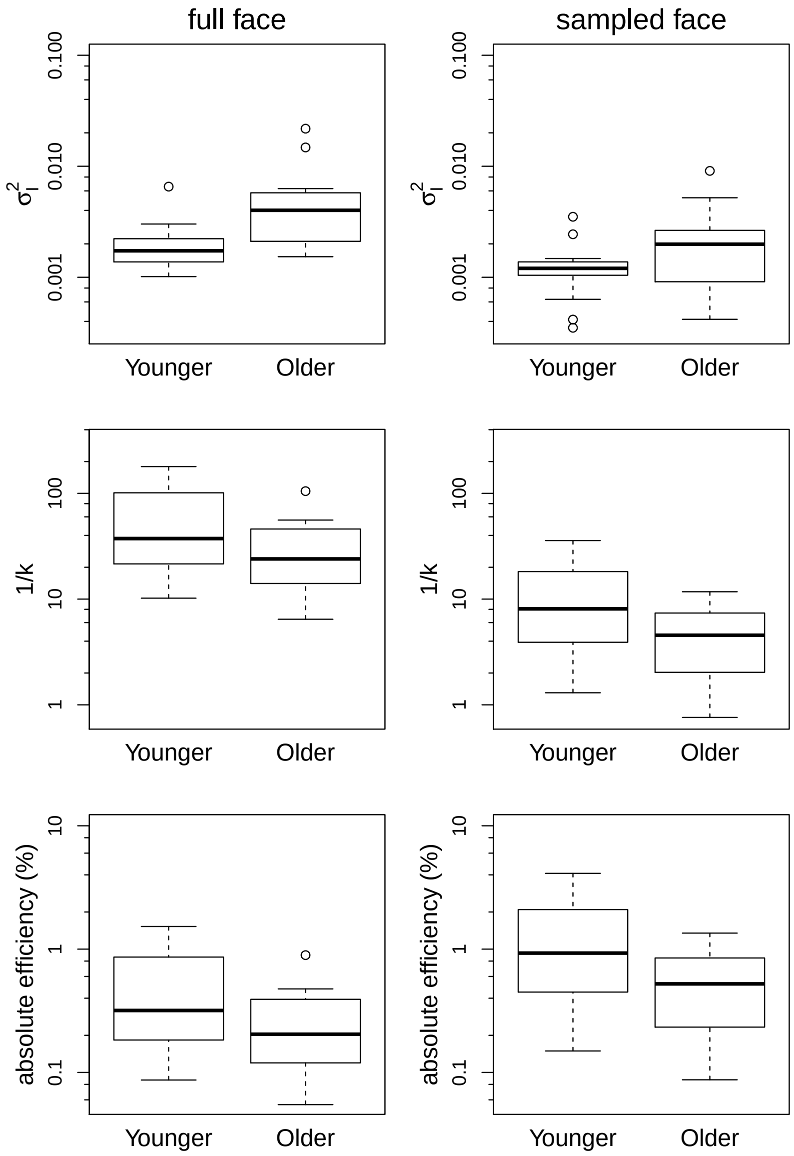

Figure 3.5 – Box plots of the parameters estimated by Equation 3.1. The top and middle panels plot equivalent input noise (σ_I^2) and $1/k$. The bottom panels show absolute efficiency, expressed as a percentage.

3.3.3 Discussion

We found that face discrimination thresholds were higher in older than younger adults. Age differences in noise-masking functions (Eq. 3.1) were consistent with the hypothesis that the age-related changes in face discrimination thresholds were due to the combined effects of an age-related increase in equivalent input noise and a decrease in absolute efficiency. Our analyses also suggest that the effect of age on equivalent input noise ($\eta_p^2 = .26$) was larger than the effect on absolute efficiency ($\eta_p^2 = .11$).

Recall that the slope of the noise-masking function also can be affected by sources of internal noise that are dependent upon stimulus contrast (Green, 1964; Burgess and Colborne, 1988; Spiegel and Green, 1981). In the next experiment, we measure the potential contribution of multiplicative internal noise to older and younger adults' performance on the same task. If no age-difference is found in multiplicative internal noise, this would suggest the age-related increase in the slope of the noise-masking function (i.e., parameter k) is not due to changes in multiplicative internal noise.

3.4 Experiment 2: Response consistency

3.4.1 Methods

3.4.1.1 Observers

Twenty-two younger ($M = 23.0$, $SD = 4.9$) and twenty-three older ($M = 70.8$, $SD = 5.6$) Caucasian adults participated in this experiment for either cash ($10/hour) or partial course credit. The visual and cognitive health of all participants was assessed using the same screening procedures used in Experiment 1. All observers had normal or corrected-to-normal Snellen visual acuity, and all older adults had normal MMSE and MoCA scores. Observers who previously participated either in the classification image experiment (Chapter 2) or in Experiment 1 were invited to participate in this experiment. In total, eight younger and 10 older adults were returning subjects, and thus had prior exposure to the stimuli. All participants except one younger adult (the first author, SEC) were unaware of the purpose of the experiment. Written informed consent was obtained from participants prior to starting the experiment, and protocols were approved by the McMaster University Research Ethics Board.

3.4.1.2 Apparatus & Stimuli

The apparatus, stimulus set, and sampling method were the same as that used in Experiment 1 (see Figure 3.3).

3.4.1.3 Procedure

The task was the same as in Experiment 1 with the exception that a single high level of external noise variance was used ($\sigma_E^2 = 0.09$). Stimulus contrast was adjusted with two randomly interleaved staircases, one following a 2-down/1-up rule and the other following a 3-down/1-up rule, maintaining accuracy at approximately 75%. Each staircase continued for a total of 200 trials. At the end of 400 trials, the exact sequence of stimuli (i.e., face-plus-noise) was repeated, yielding a total of 800 trials per stimulus type (i.e., full or sampled face) per day. It is important to note that the sequence of faces and noise fields were exactly the same in the two sets (i.e., "passes") of trials.

Subjects participated in the experiment over the course of two sessions held on consecutive days at approximately the same time each day. Each day, subjects completed two passes of each stimulus type, with the order of stimulus type being counterbalanced across days and subjects. Subjects were familiarized with the task by performing two blocks of practice trials at the beginning of each stimulus block. In the first block of practice trials, subjects completed 10 trials in which face contrast was constant and no noise was added to the stimulus. In the second block of practice trials, subjects completed 20 trials in which faces were embedded in the level of external noise used in the main experiment, and face contrast was varied according to a 2-down/1-up staircase. Once the actual experiment began, participants were allowed a self-timed break every 200 trials. Each day, the experimental session lasted approximately 1.5 hours.

3.4.2 Analyses

As in Experiment 1, analyses were performed in R (R Core Team, 2019), and the Huynh-Feldt (Maxwell et al., 2017) and Welch-Satterthwaite (Welch, 1947) corrections were used to adjust degrees-of-freedom and p values where appropriate.

We estimated 75% correct contrast thresholds by fitting Weibull functions to combined data from both passes and sessions. Lapse rate was allowed to vary between 0.01 to 0.02. One older observer was unable to perform the task at a sufficient level of accuracy, and was excluded from analyses. Of the remaining 22 older observers, for one older adult, the fits did not converge, and therefore the average of the last 6 reversals in each staircase was used as an estimate of threshold. Next, we derived the slope of the consistency function for each observer in each stimulus condition by calculating percent correct (across both passes), p_c, and percent agreement, p_a, between the two passes for each level of contrast presented. Maximum-likelihood minimization was used to estimate the slope, m, of the response consistency function:

$$p_c = m \log_{10}(p_a/100) + 100. \tag{3.5}$$

The value of m was then used as a proxy for the internal-to-external noise ratio (Gold et al., 1999a). As in Experiment 1, our estimates of threshold and response consistency slopes were based on the actual face and noise RMS contrasts presented to the observer rather than the nominal values that were used to create the stimuli.

3.4.3 Results

Figure 3.6 presents box plots of log-transformed contrast thresholds in each age group and stimulus condition. Although contrast thresholds were calculated for this experiment, it is not possible to make a quantitative comparison between the two stimulus types because sampling reduced external noise contrast variance by 7% relative to the unsampled noise. As a result, we evaluated the effect of Age on thresholds separately for full and sampled faces. Consistent with Experiment 1, log-transformed thresholds were higher in older than younger adults for both full ($t(41.9) = 2.23$, $d = 0.67$, $p = 0.016$, one-tailed) and sampled ($t(41.2) = 3.25$, $d = 0.98$, $p = 0.001$, one-tailed) faces.

Response consistency functions are presented in Figure 3.7 for a typical younger (left) and older (right) observer. Percent correct is plotted against percent agreement calculated at each level of stimulus contrast for full (filled symbols) and sampled (open symbols) faces for each session. Recall that for a fixed level of external noise the slope of the function varies systematically with the amount of internal noise, with shallower slopes (i.e., less response consistency) indicating a higher internal-to-external noise ratio. The slopes of the response consistency functions were computed for each observer and condition, and the group means are shown in Figure 3.8. Examination of these figures suggests the slopes were approximately 6% higher in the full face

Figure 3.6 – Box plots of log threshold contrast variance for younger and older adults in the full (left) and sampled (right) face conditions.

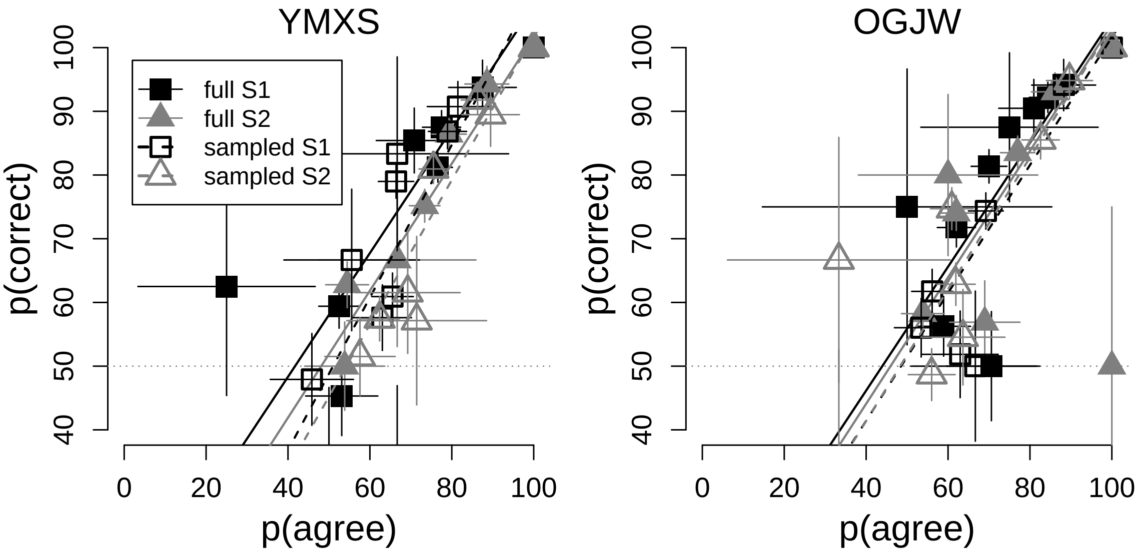

Figure 3.7 – Response consistency functions for one representative younger (left) and older (right) adult in the full (filled symbols) and sampled (open symbols) condition for each individual session.

condition than the sampled face condition, but the age differences were small and not consistent across the two stimulus types. A 2 (Age) × 2 (Stimulus Type) ANOVA on the log-transformed slopes of the response consistency function found a significant main effect of Stimulus ($F(1, 42) = 4.13$, $\eta_p^2 = .09$, $p = 0.05$). However, the main effect of Age ($F(1, 42) = 0.003$, $\eta_p^2 < .0001$, $p = 0.954$) and the Age × Stimulus interaction ($F(1, 42) = 0.12$, $\eta_p^2 = .003$, $p = 0.73$) were not significant.

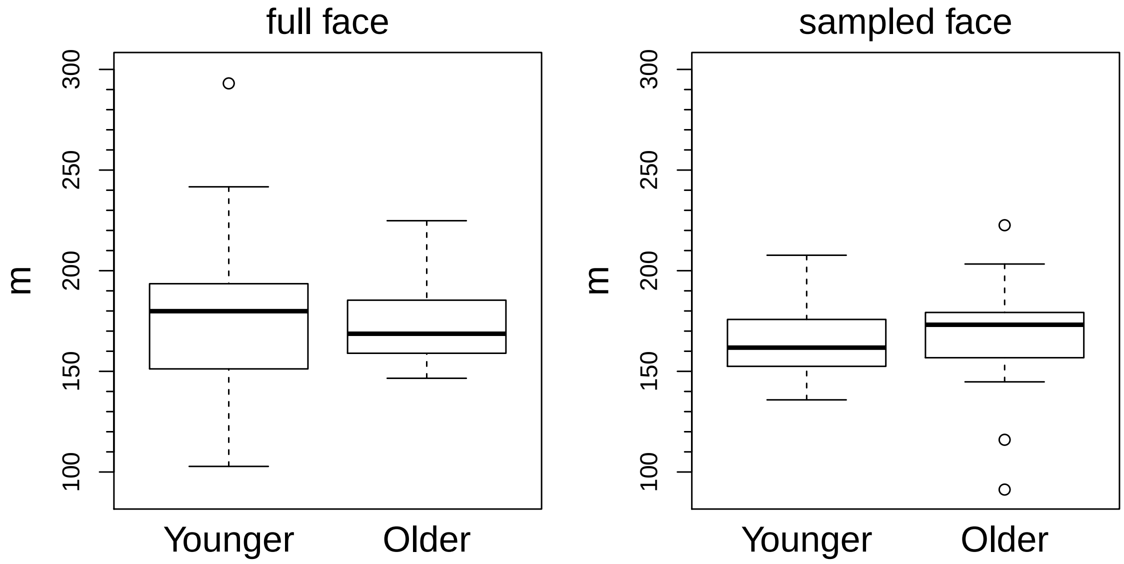

Figure 3.8 – Box plots of the parameter estimated by Equation 3.5 for younger and older adults in the full (left) and sampled (right) face conditions. Note that the y axis ranges from 100 to 300.

3.4.4 Discussion

The current experiment failed to find any evidence that response consistency differed between older and younger adults. Indeed, the size of the main effect of age was exceedingly small ($\eta_p^2 < .0001$), so the failure to obtain a significant difference was not due to a lack of statistical power. Recall that the slope of the consistency function is an index of the internal-to-external noise ratio. In the high-noise conditions used in this experiment, internal noise in both age groups should consist primarily of contrast-dependent, or multiplicative, internal noise. Thus, the failure to find age differences in response consistency suggest that the magnitude of contrast-dependent internal noise does not differ significantly between younger and older adults. In addition, there is evidence that differences in multiplicative internal noise may contribute to differences in performance for full and sampled faces.

3.5 General Discussion

We examined how older adults' ability to discriminate two faces is affected by internal noise and the efficiency with which they extract information using two complementary approaches: noise-masking and response consistency. By measuring thresholds in several levels of external noise, Experiment 1 found that older adults had higher equivalent input noise and lower efficiency compared to younger adults. Using the double-pass method (Green and Swets, 1966), Experiment 2 found that the slope of the response accuracy-vs.-consistency function was essentially identical in older and younger adults. This result implies that the internal-to-external noise ratio was the same in the two age groups, and that contrast-dependent (i.e., multiplicative) internal noise did not vary with age. Furthermore, the failure to find an age difference in response consistency implies that the age difference in efficiency that was observed in Experiment 1 was not due to age differences in contrast-dependent internal noise. In summary, we found that older adults had higher face discrimination thresholds, higher additive internal noise, and lower calculation efficiency relative to younger adults.

Previous work in aging using these approaches have found evidence of an age-related increase in equivalent input noise for motion detection (Bennett et al., 2007), direction discrimination (Bennett et al., 2007; Bogfjellmo et al., 2013; Bower and Andersen, 2012), orientation discrimination (Betts et al., 2007), and detection of sine wave gratings at high (10 cpd) spatial frequencies (Pardhan, 2004). Others have shown age-related decreases in efficiency for grating detection at a range (1-9 cpd) of spatial frequencies (Bennett et al., 1999; Pardhan et al., 1996; Allard et al., 2013), for motion discrimination at high speeds (Bogfjellmo et al., 2013), and for vernier acuity (Li et al., 2012). To our knowledge, the current study is the first to use noise-masking and response consistency to examine the effects of aging on face discrimination. However, the equivalent input noise approach has been used to study face discrimination in schizophrenic patients, whose performance also is hypothesized to be more constrained by internal noise (Winterer et al., 2000; Rolls et al., 2008). In a delayed match-to-sample task, Christensen et al. (2013) found patients with schizophrenia had increased equivalent input noise relative to neurotypical controls when discriminating upright faces. This result is similar to our Experiment 1, where we found older adults to have higher additive internal noise. However, Christensen et al. (2013) found similar values of k in schizophrenic and control subjects, whereas we found an age-related decrease in absolute efficiency. Further, our Experiment 2 was able to rule out the contribution of contrast-dependent internal noise to group differences in the slope of the noise-masking functions, whereas the influence of this type of noise cannot be extracted from the values of k reported in Christensen et al. (2013).

One curious finding is that estimates of internal noise and efficiency differed between full and sampled faces. We chose to measure performance with full and sampled faces to make it easier to compare the current results to those reported by Creighton et al. (2019) and to previous studies (Gaspar et al., 2008; Gold et al., 2004, 1999a) of equivalent input noise and response consistency. One key difference between the two types of stimuli is that the spatial extent of the noise differs. For sampled faces, it was highly localized – the noise is presented only in the sampled pixels falling within the oval that contained the face – whereas the noise extended across the entire image matrix for full faces. Allard and Cavanagh (2011) suggested that a difference in the spatial and temporal extents of the noise (relative to the target) may affect processing, and argue that using spatio-temporally extended noise is more similar to the internal noise within our visual system. In support of this idea, Allard et al. (2013) found that age differences in contrast sensitivity at lower spatial frequencies critically depended on the type of noise. Specifically, Allard et al. found that age differences in contrast sensitivity were attributable to decreased efficiency when using “local” or circumscribed external noise, consistent with prior studies (Bennett et al., 1999; Pardhan, 2004), but to increased equivalent input noise when using extended external noise. However, we found that the age difference in the noise-masking parameters did not significantly differ between the full and sampled conditions. In other words, the age differences in internal noise and calculation efficiency observed in the current study were *not* due to the spatial extent of the noise used in these experiments. However, it is important to note that our manipulation of the “spatial extent” of external noise differs considerably from the manipulation used by Allard et al. (2013). Indeed, those authors would likely consider our full and sampled noise conditions as local noise. Clearly it is of interest to directly compare the effects that various spatial and temporal manipulations of external noise have on estimates of equivalent input noise and efficiency.

Chapter 2 measured classification images (CIs) in a face discrimination task and found that many older adults' CIs lacked clear spatial structure. Recall that the expected value of a linear observer's CI is proportional to the observer's template (Murray et al., 2005), and the value of the cross-correlation between an observer's classification image and the ideal template, which is associated with absolute efficiency, is affected by both internal noise and calculation efficiency. That is, observers who use templates more closely matched to the ideal observer, and who have relatively less internal noise, will have classification images with more apparent spatial structure and relatively higher signal-to-noise ratios (SNRs). The results of Experiment 1 suggest there is an age difference in contrast-independent (i.e., additive) internal noise. However, the face stimuli in Chapter 2 were always presented in high levels of external noise where the influence of additive internal noise is negligible. Furthermore, the results of Experiment 2 suggest that there is no significant age difference in contrast-dependent (i.e., multiplicative) internal noise. Together, these results provide strong evidence that age differences in calculation efficiency produced the age differences in CIs reported in Chapter 2. In other words, the spatial structure of the CIs, and lower cross-correlation with the ideal linear template in that study are likely attributable to an age-related decrease in calculation efficiency, which might reflect differences in the strategies that are used by older and younger adults to discriminate faces.

To summarize, the current set of experiments assessed the relative contributions of internal noise and calculation efficiency on older adults' ability to discriminate between two faces. In combination, the noise-masking and response consistency paradigms indicate both additive internal noise and calculation efficiency contribute, and that age differences in the spatial structure of CIs observed in Chapter 2 result primarily from an age-related decline in efficiency of information use.

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Chapter 4

Age-related changes in orientation bias for face identification

4.1 Abstract

Younger observers use horizontal structure in the eyes/eyebrows when identifying faces, and the extent to which they do so is correlated with identification performance (Pachai et al., 2013). Several studies have shown poorer discrimination of horizontally filtered faces in older relative to younger adults, suggesting that older observers use diagnostic horizontal information less efficiently when the target band is specified precisely. However, it is unknown whether the age-related decline in face identification accuracy is related to a reduced ability to selectively utilize horizontal structure. We examined this issue using a 6AFC identification paradigm in which the target face was filtered on a given trial to retain information in only horizontal, vertical, or oblique orientations of various bandwidths. In addition, informative structure was presented either in isolation or embedded within a non-informative facial context. Age differences in horizontal bias were most reliably produced in the presence of facial context, suggesting prior studies may underestimate the size of the effect in older observers. Consistent with previous research, we found that older observers were less efficient than younger observers at utilizing horizontal structure. However, our results also suggest horizontal bias cannot completely account for age differences in face identification.

4.2 Introduction

The ability to discriminate and identify faces shows an age-related decline that cannot wholly be explained by changes in the optics of the eye (Owsley et al., 1981; Bieniek et al., 2013; Bennett et al., 1999), non-face object recognition (Boutet and Faubert, 2006; Hildebrandt et al., 2013; Meinhardt-Injac et al., 2014), or general cognitive functioning (Hildebrandt et al., 2011). Although several perceptual and cognitive factors have been hypothesized to contribute to age-related changes in face perception (see Boutet et al., 2015 for an overview), it remains unclear which visual mechanisms contribute most to this age difference. Several characteristics of face perception exhibited by younger adults can be viewed as consequences of perceptual learning, whereby observers become more efficient at extracting the information diagnostic for a given task (Gauthier and Tarr, 1997; Gold et al., 2004; Heisz and Shore, 2008; Tanaka, 2001). For example, information diagnostic for static upright face identification is most heavily concentrated in a narrow band of horizontally oriented spatial frequency components (Dakin and Watt, 2009; Goffaux and Dakin, 2010; Pachai et al., 2018), and younger adults that rely relatively more heavily on that facial structure identify upright faces more accurately (Pachai et al., 2013). Such horizontal biases have been linked to performance in several tasks that are thought of as behavioural markers of face perception (Goffaux and Dakin, 2010). In this paper we examine the hypothesis that age-related deficits in face identification reflect a decrease in the efficiency with which older observers encode task-relevant horizontal facial structure.

Several studies have examined how the orientation bias for face identification changes during healthy aging (Obermeyer et al., 2012; Goffaux et al., 2015; Schaich et al., 2016; Obermeyer et al., 2017) and in older adults with central visual field loss (Yu and Chung, 2011). Like younger observers, older adults preferentially rely on horizontal facial structure over other orientations when judging the identity of unfamiliar (Goffaux et al., 2015; Obermeyer et al., 2012) and familiar (Yu and Chung, 2011) faces, and some evidence suggests this orientation bias may be stronger in upright than inverted faces (Goffaux et al., 2015, though see Obermeyer et al., 2012). However, it remains unclear whether reduced horizontal bias *per se* is the reason that face identification is worse in older than younger adults. In a semi-delayed face matching task, Goffaux et al. (2015) examined how horizontal bias and the face inversion effect (FIE) develop over the lifespan by filtering unfamiliar faces to retain either horizontal

(H), vertical (V), or a sum of the two (H+V). Although the H+V condition contained both horizontal and vertical structure, the filter bandwidth (20° FWHM) used in this study did not pass all orientations, and thus performance in the H+V condition may not be comparable to identification of unfiltered faces. In addition, Goffaux et al. did not assess the association between the H+V condition and horizontal bias. Obermeyer et al. (2012) showed that older adults had somewhat poorer memory for unfiltered upright faces compared to younger adults, and that the difference between performance with horizontally- and vertically-filtered faces was smaller in older than younger adults. Based on these results, Obermeyer et al. concluded that age-related changes in face recognition were caused by age differences in the horizontal bias of face processing, but they also did not directly test whether individual differences in horizontal bias were associated with face recognition accuracy. In a follow-up study, Schaich et al. (2016) found that face recognition was poorer in older adults than younger adults for both unfiltered and horizontally filtered faces, and that performance in these two conditions were positively correlated in younger, but not older adults. This result suggests that sensitivity to horizontal structure is important for identification in younger but not older adults. However, Schaich et al. did not include a vertically-filtered face condition, and therefore it is possible that any type of orientation filtering might disrupt face processing in older adults. This is an important distinction, because faces contain information at all orientations (Pachai et al., 2018), and identification performance in the unfiltered condition relies on one's ability to efficiently extract the most diagnostic orientation band. Thus, no study to date has convincingly demonstrated that age-related declines in the relative reliance (i.e., bias) on horizontal over other orientations is associated with age-related declines in face identification.

Using an ideal observer, Pachai et al. (2018) demonstrated that the extra identity information conveyed by horizontal structure (i.e., the horizontal advantage) is found for a narrow range (≈10°) of near-horizontal orientations, at least for the faces used in their study. Information outside of this narrow band, while still informative, did not appreciably increase the magnitude of the horizontal advantage for the ideal observer. On the other hand, the horizontal bias in younger adults continues to increase up to a bandwidth of ≈70°. This result suggests that, although the most diagnostic identity information is carried by a small subset of information centred around horizontal, younger observers integrate information over a broader range of orientations when identifying faces. The aging studies discussed above used Gaussian filters with standard deviations ranging between 20° (Goffaux et al., 2015) and 23° (Obermeyer et al., 2012; Yu and Chung, 2011; Schaich et al., 2016) and were held constant throughout the experiment, and it is likely that older observers integrate orientation information over an even broader band than younger observers. If true, we might expect age differences in horizontal bias to become even more pronounced for a condition that embeds the signal orientations within an uninformative context. For example, in a 1-of-6 face identification task, a stimulus could contain diagnostic structure for the target identity in an orientation band of bandwidth b deg centred on orientation o, and non-diagnostic structure from the pixelwise average of all six faces in the remaining orientation bands. In this scenario, observers must discover the maximally diagnostic task-relevant orientation structure. If older observers use structure at a range of orientations that is greater than b and/or centered on an orientation other than o to identify faces, then we would expect the introduction of non-informative context to have a larger impact on older than younger adults. In partial support of this idea, some studies suggest older adults are more affected by the context in which a face is presented (Konar et al., 2013; Meinhardt-Injac et al., 2014; Chaby et al., 2011), and that the degree to which older observers are unable to optimally weight relevant contextual information is correlated with worse face identification (Konar et al., 2013).

In the current experiments, we assessed the extent to which older observers preferentially rely on horizontal spatial structure by measuring identification accuracy for faces that were filtered to retain horizontal (0°), vertical (90°), or oblique (±45°) orientations, and whether horizontal bias is associated with age-related deficits in face identification. To determine the range over which younger and older observers extract and integrate oriented facial structure we used orientation bandwidths of 45° and 90°. In addition, the informative oriented structure was either presented by itself (Context Absent) or embedded in a non-informative facial context (Context Present). Embedding the informative oriented structure within a non-informative context meant that stimuli in the Context Present condition more closely resembled unfiltered faces and therefore were more likely to engage normal face processing.

4.3 Experiment 1

4.3.1 Methods

4.3.1.1 Observers

Experiment 1 included two between-subjects variables: filter bandwidth (narrow vs. wide) and stimulus context (present vs. absent). We tested separate groups of younger and older adults with each combination of filter bandwidth and stimulus context. In the narrow bandwidth condition we tested 12 younger (M = 20.7, SD = 2.1, 4 males) and 13 older (M = 70.0, SD = 7.3, 7 males) adults in the context present condition, and 12 younger (M = 24.3, SD = 3.8, 4 males) and 13 older (M = 69.9, SD = 6.0, 7 males) adults in the context absent condition[1]. In the wide bandwidth condition we tested 13 younger (M = 19.8, SD = 2.4, 4 males) and 13 older (M = 67.5, SD = 6.0, 8 males) adults in the context present condition, and 13 younger (M = 19.3, SD = 1.3, 1 male) and 13 older (M = 66.4, SD = 5.1, 4 males) adults in the context absent condition. All observers were Caucasian and had normal or corrected-to-normal Snellen visual acuity. Also, all of the observers were unpracticed, were naïve to the purpose of the experiment, and had no prior exposure to the stimuli. Younger adults were students at McMaster University and were paid $10 per hour or received partial course credit for participating. Older adults were recruited from the local community and were paid $10 per hour for their participation. Participants were screened for visual pathologies with a vision and general health questionnaire. The Mini Mental State Examination (Folstein et al., 1975) and the Montreal Cognitive Assessment (Nasreddine et al., 2005) were used to screen for cognitive impairments; MMSE and MoCA scores fell within the normal range. The McMaster University Research Ethics Board approved the experimental protocol and written informed consent was obtained prior to initiation of the experiment.

4.3.1.2 Apparatus

Stimuli were generated using an Apple Macintosh G5 computer using MATLAB with the Psychophysics and Video Toolboxes (Brainard, 1997; Pelli, 1997), and presented

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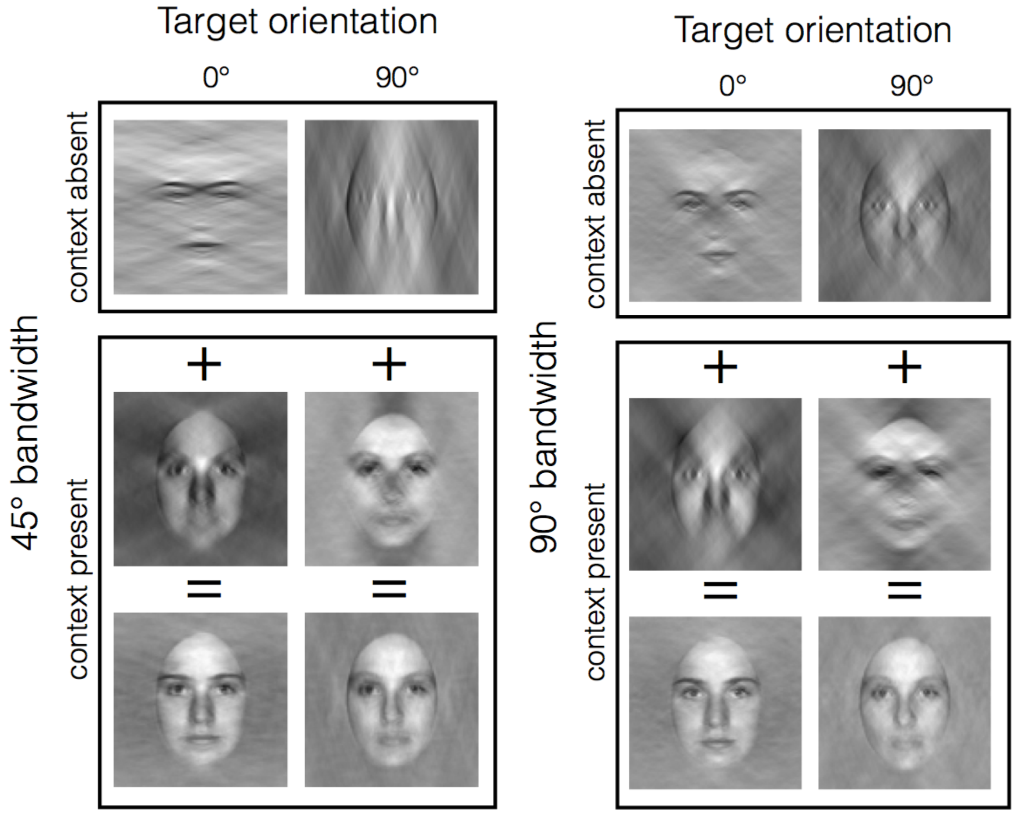
[1] One participant in each of the two groups of younger adults was accidentally counted twice due to experimenter error and therefore the final sample sizes were 12 instead of 13.

on a 21” Apple Studio display (41 cm × 31 cm) with a resolution of 1152 × 870 pixels and a frame rate of 75 Hz. Average luminance was 18.5 cd/m^2. A chin rest stabilized head position throughout the experiment, maintaining a viewing distance of 60 cm. The monitor was the only source of light in the room.

4.3.1.3 Stimuli

Stimuli were based on front-facing digitized photographs of three male and three female Caucasian faces lacking piercings, facial hair, and glasses. Each face was centred in a 256 × 256 pixel array (8.6° × 8.6° visual angle) and cropped using a 198 × 140 pixel oval window to isolate the internal facial features. The amplitude spectrum of each individual face was replaced with the average amplitude spectrum of the ten original faces prior to experimental manipulation. Additional details on stimulus creation can be found in Gold et al. (1999).

Across trials, the orientation information available to observers for face identification was manipulated by filtering the stimuli in the Fourier domain. Specifically, an ideal bandpass filter of full bandwidth, b, equal to 45° (narrow bandwidth) or 90° (wide bandwidth) was used to isolate frequency components in the target face $\pm b/2°$ from orientations centred on 0° (horizontal), 90° (vertical), or ±45° (obliques). In the Context Absent condition, the stimuli contained only spatial frequency components that were passed by the orientation filter, and therefore the stimulus consisted entirely of informative structure. In the Context Present condition, the filtered spatial frequency components from a target face were combined with a facial context that was constructed by averaging the frequency components from all six faces that fell *outside* the orientation filter bandwidth. Because the components were averaged across all faces, the context provided no information about the identity of the target face. The amplitudes of the spatial frequency components of the target face were scaled such that the total power of the final Context Present face was equal across filter conditions. The RMS contrast of the face stimulus was 0.3. Finally, white noise with an RMS contrast equal to 0.01 was added to the face stimulus. Examples of Context Absent and Context Present stimuli are shown in Figure 4.1.



(a) 45° (Narrow) bandwidth condition **(b)** 90° (Wide) bandwidth condition

Figure 4.1 – Examples of stimuli used in Experiment 1. The top rows in each panel show target faces filtered to retain orientation structure centred on 0° (horizontal) or 90° (vertical) in the narrow (45°) bandwidth (a) and wide (90°) bandwidth (b) conditions. The experiment also used unfiltered stimuli and stimuli filtered to retain structure at ±45° (not shown). Context Absent stimuli are simply the orientation filtered target face (top rows in each panel). Context Present (bottom rows in each panel) stimuli are the pixelwise addition of the orientation filtered target (Context Absent) and orthogonal orientation structure from the average of all six faces (middle rows in each panel).

4.3.1.4 Procedure

Prior to beginning the experimental trials, participants were adapted to the average luminance of the display for 30 s and then completed 10 practice trials to familiarize themselves with the task. On each trial, a target face was randomly selected and then filtered according to a randomly selected orientation condition. Each trial consisted of a central fixation dot presented for 500 ms, followed by a 500 ms presentation of the target face and then a response screen that contained a 2×3 matrix of the six possible identities which were filtered in the same way as the target face. For example, if the target face on the trial was horizontally filtered, then all faces on the response screen were horizontally filtered. Observers responded by clicking a computer mouse on one of the images, and auditory feedback, in the form of high- and low-pitched tones, was presented for correct and incorrect responses, respectively. Observers completed a total of 500 trials (100 trials per filter condition) split across two blocks of 250 trials each. Subjects were allowed to take a self-timed break halfway through each block.

4.3.1.5 Design & Analysis

Each participant was tested with five types of stimuli: unfiltered faces and four types of orientation-filtered faces (i.e., filter orientations of 0, ±45, and 90 deg). Stimulus types were interleaved during testing. Context (present/absent), age (younger/older), and bandwidth (narrow/wide) were between-subjects factors. The dependent measure was proportion correct.

Statistical analyses were performed in R (R Core Team, 2019). F tests conducted on within-subjects factors used degrees-of-freedom and p values that were adjusted with the Huynh-Feldt correction for departure from sphericity (Maxwell et al., 2017). Two-sample t tests used degrees-of-freedom that were adjusted using the Welch-Satterthwaite correction for unequal variances (Welch, 1947). Unless noted otherwise, two-tailed tests are reported. Cohen's d and partial eta-squared (η_p^2) are reported as measures of effect size and association strength, respectively.

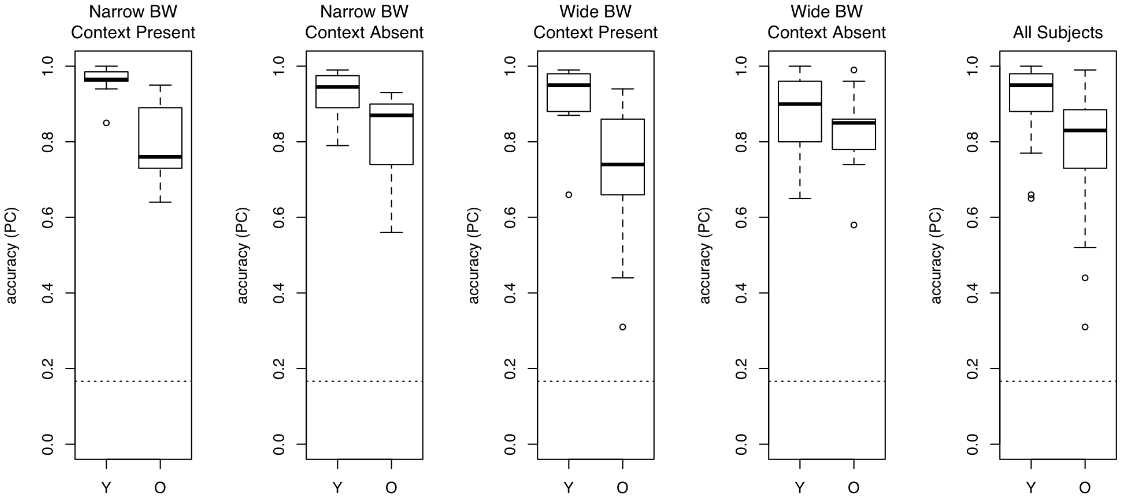


Figure 4.2 – Response accuracy for unfiltered faces in Experiment 1. The rightmost plot shows data from all subjects, and the other four plots show accuracy measured for different groups of younger (Y) and older (O) participants who were assigned to the various filtered stimuli conditions (i.e., narrow vs. wide orientation filters & context present vs. context absent). The horizontal dashed line in each plot indicates chance performance. Median response accuracy was consistently lower in older than younger participants.

4.3.2 Results

4.3.2.1 Identification of Unfiltered Faces

Response accuracy in the unfiltered face condition in each of the eight groups is shown in Figure 4.2. Average response accuracy was 0.92 (range = $[0.87,\ 0.96]$) in the four groups of younger adults and 0.79 (range = $[0.72, 0.83]$) in the four groups of older adults. Although the unfiltered faces were the same for all conditions illustrated in Figure 4.2, they were intermixed with stimuli that differed in terms of filter orientation. To see if accuracy for unfiltered faces varied across conditions, we analyzed the data in Figure 4.2 with a 2 (Age Group) × 2 (Bandwidth) × 2 (Context) ANOVA[2]. The ANOVA revealed a significant main effect of Age ($F(1,94) = 36.02$, $\eta_p^2 = 0.28$, $p < .0001$) and a significant Age × Context interaction ($F(1,94) = 5.62$, $\eta_p^2 = 0.06$, $p = .02$). The main effect of Bandwidth was not significant ($F(1,94) = 2.96$, $\eta_p^2 = 0.03$, $p = .09$), nor were the other two- and three-way interactions ($F \leq 1.47$, $\eta_p^2 \leq .02$, $p \geq .23$ in each case).

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[2] All of the analyses reported in this paper also were performed on arcsine-transformed proportion correct. The results of the two sets of analyses were always very similar, so we report only the results obtained from analyses of untransformed proportion correct.

Follow-up analyses indicated that the age difference was significant in the Context Present ($t(35.6) = 5.47$, $d = 1.52$, $p < .001$) and Context Absent ($t(46.5) = 2.76$, $d = 0.77$, $p = .008$) conditions. Hence, we found that identification of unfiltered faces was significantly less accurate in older adults than younger adults, and that the age difference was slightly larger in the Context Present condition.

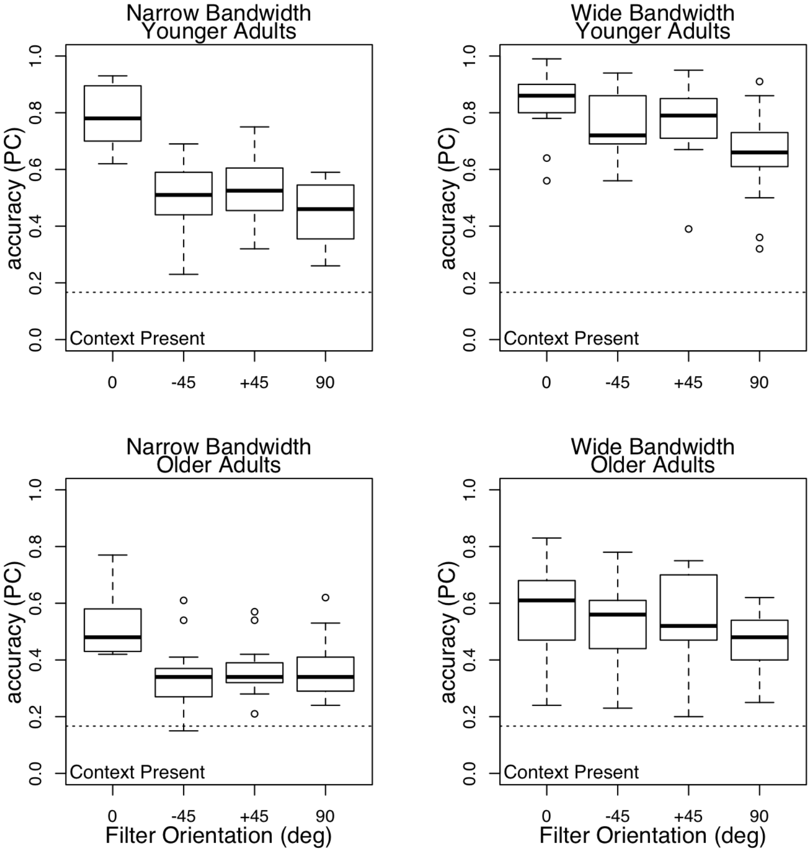


Figure 4.3 – Boxplots illustrating the distribution of response accuracy in Experiment 1 for filtered faces for younger (top row) and older adults (bottom row) in the Context Present condition. Results obtained with narrow and wide orientation bandwidths are shown in the left and right columns, respectively. Each panel shows accuracy for four filter orientations.

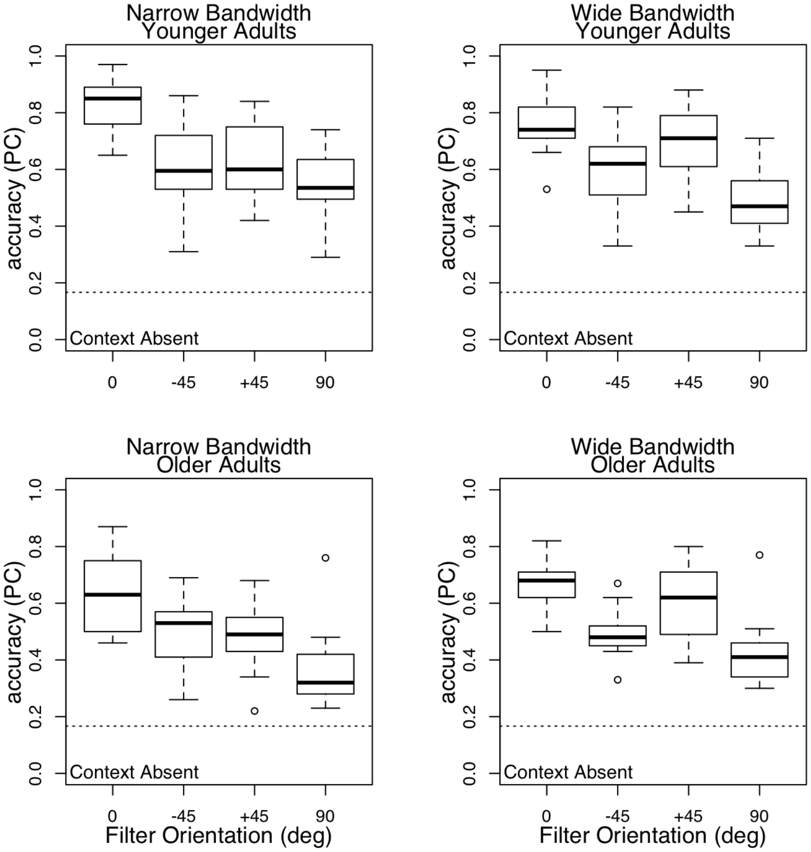


Figure 4.4 – Boxplots illustrating the distribution of response accuracy in Experiment 1 for filtered faces for younger (top row) and older adults (bottom row) in the Context Absent condition. Results obtained with narrow and wide orientation bandwidths are shown in the left and right columns, respectively. Each panel shows accuracy for four filter orientations.

4.3.2.2 Orientation Filtered Faces

Accuracy in the filtered face conditions are shown in Figures 4.3 and 4.4. As in the unfiltered face condition, accuracy generally was higher in younger adults than older adults. In addition, accuracy in both age groups tended to be higher in the horizontal filter condition than the vertical filter condition, although this effect of orientation was slightly greater in younger than older adults. The effect of filter orientation also was smaller in the wide bandwidth condition compared to the narrow bandwidth condition; however, this effect is not unexpected because increasing filter bandwidth caused the stimuli in the various filter conditions to become more similar. In the context present condition (Figure 4.3), accuracy in both age groups was higher in the wide bandwidth condition than the narrow bandwidth condition; however, this effect of filter bandwidth appeared to be smaller in the context absent condition (Figure 4.4).

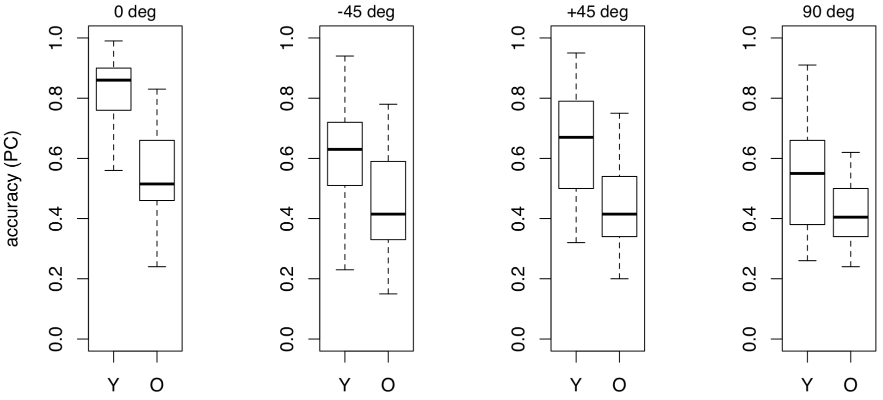
The data in Figures 4.3 and 4.4 were analyzed with a 2 (Age) × 4 (Filter Orientation) × 2 (Context) × 2 (Bandwidth) mixed ANOVA (see Table 4.1). The main effects of Age, Bandwidth, and Filter Orientation were significant; however, these main effects were qualified by significant three-way interactions between Bandwidth, Context, and Filter Orientation, and between Age, Context, and Filter Orientation.

We analyzed the Bandwidth × Context × Filter Orientation interaction by collapsing the data across age groups and analyzing accuracy in the narrow and wide bandwidth conditions with separate 2 (Context) × 4 (Filter Orientation) ANOVAs. In the narrow bandwidth condition, the main effects of Context ($F(1, 48) = 6.04$, $\eta_p^2 = 0.11$, $p = .02$) and Filter Orientation ($F(2.67, 128.37) = 101.65$, $\eta_p^2 = 0.68$, $p < .0001$) were significant, but the Context × Filter Orientation interaction ($F(2.67, 128.37) = 2.67$, $\eta_p^2 = .05$, $p = .06$) was not. The main effect of filter orientation reflects the fact that accuracy was highest in the horizontal condition ($M = 0.69$), intermediate in the left ($M = 0.48$) and right ($M = 0.50$) oblique conditions, and lowest in the vertical condition ($M = 0.43$). The main effect of context reflects the fact that accuracy was higher in the context absent ($M = 0.57$) condition than the context present ($M = 0.478$) condition. Moreover, the difference between accuracy in the context absent and present conditions was similar at each filter orientation, ranging from a low of 0.046 in the vertical condition to a high of 0.13 in the left oblique ($-45\,\mathrm{deg}$) condition. In the wide bandwidth condition, there was a significant main effect of Filter Orientation ($F(2.37, 118.49) = 68.4$, $\eta_p^2 = .58$, $p < .0001$) and a significant Context × Filter Orientation interaction ($F(2.37, 118.49) = 6.29$, $\eta_p^2 = .11$, $p = .001$). The main effect of Context was not significant ($F(1,50) = 1.54$, $\eta_p^2 = .03$, $p = .22$). As was the case in the narrow bandwidth condition, accuracy was highest in the horizontal condition ($M = 0.71$), intermediate in the left ($M = 0.60$) and right ($M = 0.65$) conditions, and lowest in the vertical condition ($M = 0.50$). The two-way interaction reflects the fact that the difference between accuracy in the context absent and present conditions was nearly zero in the horizontal and right oblique conditions, but was negative (i.e., accuracy was lower in the context absent condition) in the left oblique ($M = -0.10$) and vertical ($M = -0.09$) conditions. Note that the direction of this context effect is opposite to the context effect found in the narrow bandwidth condition. In summary, for both narrow and wide filter bandwidths and context present and absent conditions, accuracy was highest in the horizontal condition, intermediate for the left and right oblique condition, and lowest in the vertical condition. In the narrow bandwidth condition, accuracy was slightly higher in the context absent condition at all filter orientations. In the wide bandwidth condition, accuracy was lower in the context absent condition for filter orientations of -45 and 90 deg (i.e., left oblique and vertical) but not for filter orientations of 0 and 45 deg (i.e., horizontal and right oblique).

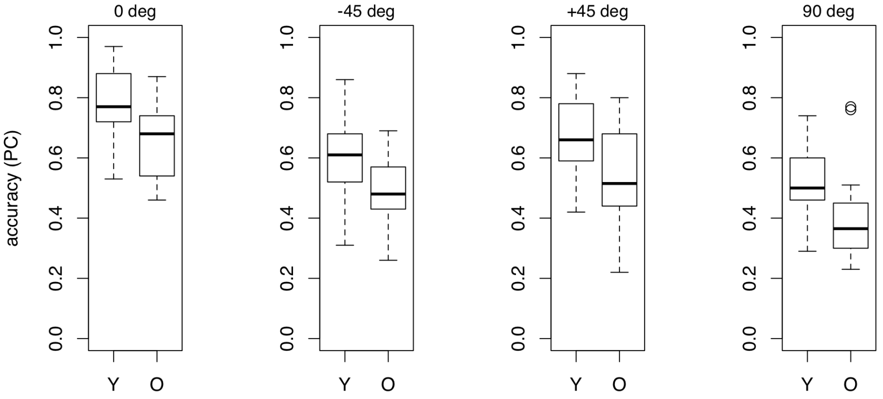
The ANOVA on accuracy for filtered faces also found a significant interaction between Age, Context, and Filter Orientation (Table 4.1). The interaction is depicted graphically in Figure 4.5, which shows response accuracy in younger and older participants, after averaging across bandwidth conditions, for each filter orientation in the context present and absent conditions. A 2 (Age Group) × 4 (Filter Orientation) ANOVA on data from the context present condition found significant main effects of age ($F(1,49) = 24.14$, $\eta_p^2 = 0.33$, $p < .0001$) and filter ($F(2.81, 137.46) = 59.05$, $\eta_p^2 = 0.55$, $p < .0001$), and a significant age × filter orientation interaction ($F(2.81, 137.46) = 5.54$, $\eta_p^2 = 0.10$, $p = .002$). The significant interaction reflects the fact that the magnitude of the age difference varied across filter orientation conditions, being largest in the horizontal condition ($t(47.9) = 7.05$, $d = 1.97$, $p < .0001$), intermediate in the left ($t(48.07) = 3.97$, $d = 1.11$, $p < .001$) and right ($t(48.04) = 4.02$, $d = 1.13$, $p < .001$) oblique conditions, and smallest in the vertical condition ($t(41.13) = 3.07$, $d = 0.86$, $p = 0.004$). In the context absent condition, a 2 (Age Group) × 4 (Filter Orientation) ANOVA yielded significant main effects of age ($F(1,49) = 19.55$, $\eta_p^2 = 0.29$, $p < .0001$) and filter orientation ($F(2.70, 132.19) = 86.32$, $\eta_p^2 = 0.64$, $p < .0001$). The age difference was significant at each filter orientation ($t \geq 3.24$, $d \geq 0.91$, $p \leq .002$ in each case) but the magnitude of the age difference did not vary significantly across filter orientations, as indicated by a non-significant age × filter orientation interaction ($F(2.70, 132.19) = 0.05$, $\eta_p^2 = 0.001$, $p = .98$). Finally, we conducted separate 2 (Age Group) × 2 (Context) ANOVAs for each filter orientation. The main effect of age was significant ($F \geq 21.37$, $\eta_p^2 \geq .18$, $p \leq .0001$) at each filter orientation. However, we found that the age × context interaction was significant ($F(1, 98) = 6.59$, $\eta_p^2 = 0.06$, $p = .01$) in the horizontal condition – the age difference was significantly larger in the context present condition – but not in the other conditions ($F \leq 1.34$, $\eta_p^2 \leq .01$, $p \geq .25$). In summary, we found that face identification accuracy was lower in older adults at all filter orientations in both the context present and context absent conditions, that the size of the age difference varied significantly with filter orientation in the context present condition ($M = 0.192$, range = $[0.128, 0.257]$) but was nearly constant ($M = 0.125$, range = $[0.122, 0.133]$) across filter orientations in the context absent condition, and that the age difference was significantly larger in the context present condition than the context absent condition with faces filtered with horizontal filters but not with other filter orientations.

Table 4.1 – Results from the Age (A) × Filter Orientation (FO) × Context (C) × Bandwidth (B) ANOVA on proportion correct data from Experiment 1.

Effect	**df**	**MSE**	***F***	$\boldsymbol{\eta_p^2}$	***p***
A	1, 94	0.05	53.22	.36	<.0001
B	1, 94	0.05	17.23	.15	<.0001
C	1, 94	0.05	1.05	.01	.31
A × B	1, 94	0.05	0.02	<.01	.88
A × C	1, 94	0.05	2.14	.02	.15
B × C	1, 94	0.05	10.44	.10	.002
A × B × C	1, 94	0.05	1.94	.02	.17
FO	2.71, 254.98	0.01	168.90	.64	<.0001
A × FO	2.71, 254.98	0.01	3.80	.04	.01
B × FO	2.71, 254.98	0.01	13.52	.13	<.0001
C × FO	2.71, 254.98	0.01	4.59	.05	.005
A × B × FO	2.71, 254.98	0.01	1.87	.02	.14
A × C × FO	2.71, 254.98	0.01	2.67	.03	.05
B × C × FO	2.71, 254.98	0.01	4.56	.05	.005
A × B × C × FO	2.71, 254.98	0.01	1.04	.01	.37



(a) Context Present



(b) Context Absent

Figure 4.5 – Boxplots illustrating the Age × Filter Orientation × Context interaction found in Experiment 1 (see Table 4.1). Each plot depicts the distributions of response accuracy in younger (Y) and older (O) adults for one filter orientation after averaging data across bandwidth conditions. Data from the context present and absent conditions are shown in the top and bottom rows, respectively. The group difference was statistically significant in every case.

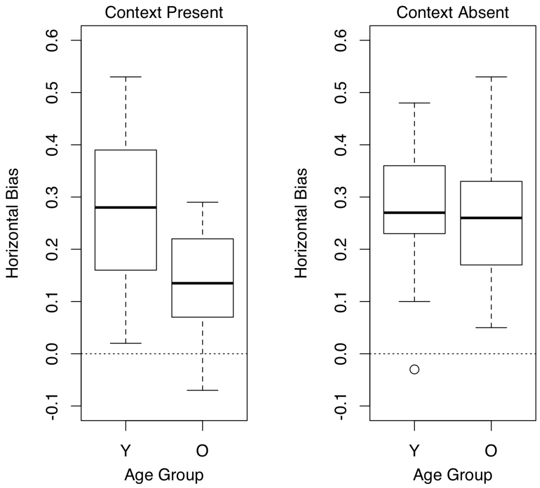
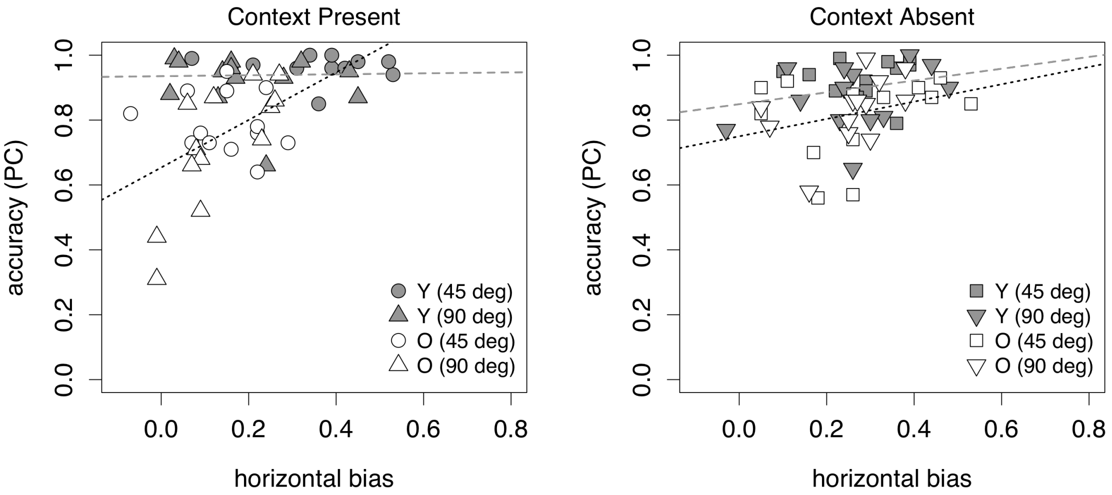


Figure 4.6 – Boxplots of horizontal bias measured in younger (Y) and older (O) adults in the Context Present and Absent conditions in Experiment 1 after averaging data in the narrow and wide bandwidth conditions. Horizontal bias was defined as difference between accuracy in the horizontal and vertical filter orientation conditions.

4.3.2.3 Identification vs. Horizontal Bias

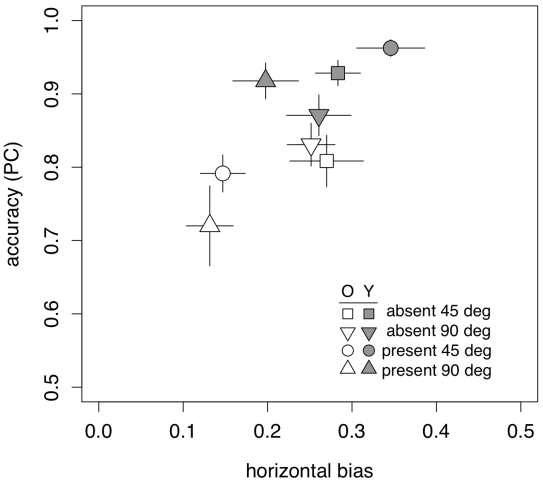
We defined horizontal bias for each observer as the difference between accuracy in the horizontal and vertical filter orientation conditions. A 2 (Age Group) × 2 (Context) × 2 (Bandwidth) ANOVA on the horizontal bias scores yielded a significant intercept ($F(1,94) = 373.86$, $\eta_p^2 = 0.80$, $p < .0001$), demonstrating that the grand mean of the horizontal bias scores differed significantly from zero. The main effect of bandwidth was significant ($F(1,94) = 4.39$, $\eta_p^2 = .04$, $p = .04$), reflecting the fact that horizontal bias was slightly greater in the narrow bandwidth condition ($M = 0.259$) than the wide bandwidth condition ($M = 0.210$). The main effects of age group ($F(1,94) = 8.68$, $\eta_p^2 = 0.08$, $p = .004$) and context ($F(1,94) = 6.23$, $\eta_p^2 = 0.06$, $p = .01$) were significant, as was the age × context interaction ($F(1,94) = 6.17$, $\eta_p^2 = 0.06$, $p = .01$). This two-way interaction is illustrated in Figure 4.6. The group difference in horizontal bias was significant in the context present condition ($t(39.635) = 3.539$, $d = 0.996$, $p = .001$) but not in the context absent condition ($t(48.73) = 0.314$, $d = 0.088$, $p = .76$), and the effect of facial context on horizontal bias was significant in older observers ($t(46.09) = 3.823$, $d = 1.06$, $p =< .001$) but not in younger observers ($t(44.26) = 0.072$, $d = 0.02$, $p = 0.94$). None of the other effects in the ANOVA were significant (in each case, $F \leq 1.97$, $\eta_p^2 \leq .02$, $p \geq .16$). In summary, the analyses suggest that horizontal bias was similar in both age groups in the context absent condition, but the presence of facial context significantly reduced horizontal bias in older adults but not younger adults.

Several studies (Pachai et al., 2013; Hashemi et al., 2019) have reported that identification accuracy for unfiltered faces is positively correlated with horizontal bias. The association between identification accuracy and horizontal bias found in the current experiment is illustrated by the scatter plots in Figures 4.7 a & b. Because we found that age differences in horizontal bias depended on the presence or absence of facial context, but not on the bandwidth of the orientation filters, we analyzed the context conditions separately but averaged data across the bandwidth conditions. In the context present condition, the overall correlation between identification accuracy and horizontal bias was significantly greater than zero ($r = 0.44$, $t(49) = 3.45$, $p < .001$, 1-tailed); however, the correlation was significant in older observers ($r = 0.46$, $t(24) = 2.53$, $p = .009$, 1-tailed) but not younger observers ($r = 0.03$, $t(23) = 0.15$, $p = .44$, 1-tailed). This age difference undoubtedly was influenced by the fact that the ceiling effect on accuracy was more pronounced in younger adults than older adults. In the context absent condition, the overall correlation between identification and horizontal bias was significantly greater than zero ($r = 0.28$, $t(49) = 2.01$, $p = .025$, 1-tailed), but was not statistically significant in either age group (younger: $r = 0.24$, $t(23) = 1.20$, $p = .121$, 1-tailed; older: $r = 0.30$, $t(24) = 1.56$, $p = .07$, 1-tailed). Mean identification accuracy and horizontal bias for each group are plotted in Figure 4.7c. Note that the positive association between identification accuracy and horizontal bias is more apparent at the group level than at the level of individual subjects. Also, Figure 4.7c suggests that it is unlikely that age differences in identification accuracy are due entirely to age differences in horizontal bias. This last point is seen most clearly in the context absent condition, where there is evidence for an age difference in identification accuracy without any apparent age difference in horizontal bias.



(a) Context present condition

(b) Context absent condition



(c) Group means

Figure 4.7 – Identification accuracy for unfiltered faces and horizontal bias measured in Experiment 1. a & b): Accuracy is plotted against horizontal bias in the context present (a) and context absent (b) conditions. Each point represents a single younger (Y) or older (O) observer in the narrow (45 deg) or wide (90 deg) bandwidth condition; dashed and dotted lines represent the least-squares regression lines fit to data from younger and older observers, respectively. c): Mean identification accuracy and mean horizontal bias in each group. Note that the vertical axis in (c) starts at 0.5, not 0. Error bars represent ±1 SEM.

4.3.3 Discussion

Consistent with previous research (Dakin and Watt, 2009; Goffaux and Dakin, 2010; Pachai et al., 2017, 2018), we found that younger adults identified upright faces more accurately when they were filtered to retain horizontal structure compared to vertical structure. Older adults also were more accurate when faces contained informative horizontal structure. However, unlike what was found in younger observers, the size of the horizontal bias in older adults depended on the presence or absence of non-informative facial context. Specifically, horizontal bias was equivalent in older and younger adults when the informative stimulus structure was shown by itself, but horizontal bias was significantly less in older adults when the informative structure was embedded in a non-informative facial context (see Figure 4.6).

Previous studies reported that identification accuracy for unfiltered faces is positively correlated with horizontal bias (Pachai et al., 2013; Hashemi et al., 2019). At the group level, we also found that average identification accuracy was positively associated with average horizontal bias (Figure 4.7c), although the association was weaker at the level of individual subjects (Figure 4.7a & b). Our failure to find significant correlations between identification accuracy and horizontal bias in individual younger observers may be due in part to a ceiling effect on our measure of face identification: accuracy for unfiltered faces was greater than 90% correct in two-thirds of younger observers. In any case, the results of Experiment 1 suggest that it is unlikely that group differences in face identification accuracy are due entirely to group differences in horizontal bias because in the context absent condition we found significant group differences in identification even though horizontal bias was similar in the two groups (Figure 4.7c).

4.4 Experiment 2

Experiment 1 found that older adults identify faces less accurately than younger adults and that horizontal bias is lower in older than younger adults when informative face structure was embedded in a non-informative facial context. We also found that the age difference in identification accuracy for filtered faces was increased when the informative horizontal structure was embedded in a non-informative facial context. Interestingly, we found no evidence that the presence or absence of context affected the age difference in identification when the informative structure was presented at other orientations (i.e., vertical and left & right obliques). Experiment 2 attempted to replicate these findings with a different set of face stimuli.

4.4.1 Methods

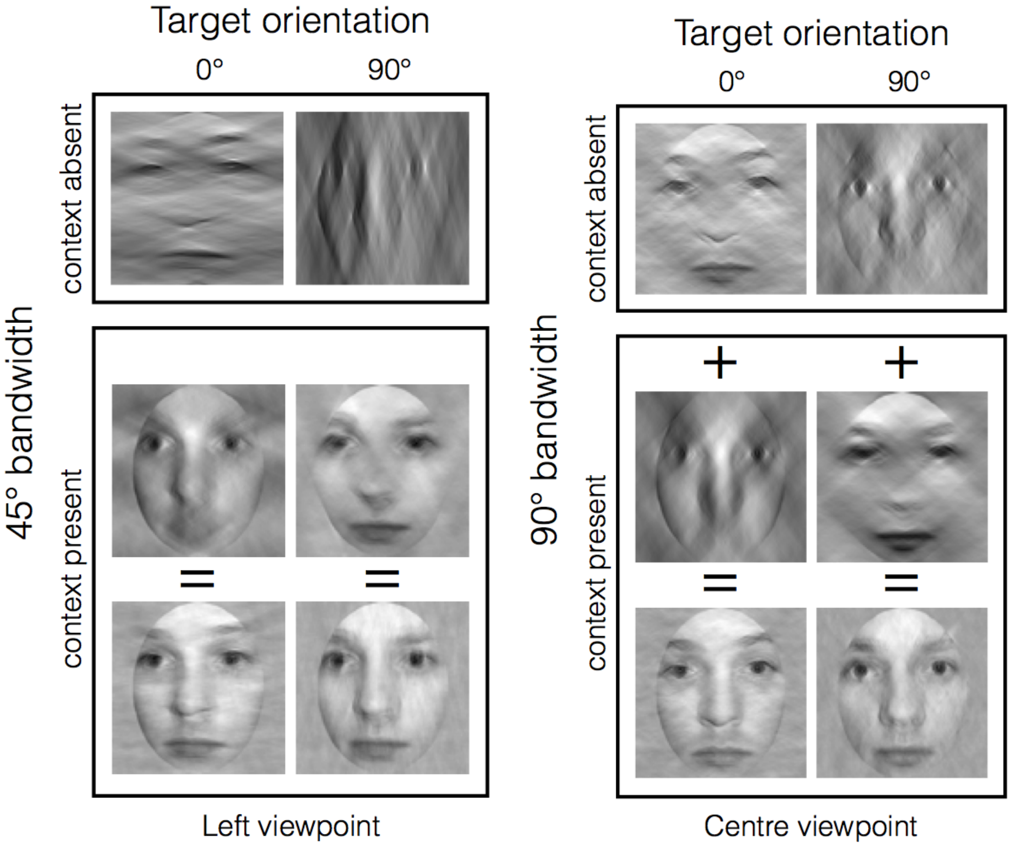
4.4.1.1 Observers

Separate groups of younger and older adults were tested with each combination of filter bandwidth (narrow vs. wide) and stimulus context (present vs. absent). In the narrow bandwidth condition we tested 12 younger (M=22.6, *SD*=3.4, 3 males) and 12 older (M=72.1, *SD*=7.0, 5 males) adults in the context present condition, and 12 younger (M=19.7, *SD*=1.2, 3 males) and 12 older (M=74.8, *SD*=7.2, 4 males) adults in the context absent condition. In the wide bandwidth condition, 12 younger (M=19.6, *SD*=2.0, 3 males) and 12 older (M=71.1, *SD*=7.0, 6 males) adults participated in the context present condition, and 12 younger (M=19.2, *SD*=0.9, 3 males) and 12 older (M=71.2, *SD*=6.9, 7 males) adults participated in the context absent condition. Observers were Caucasian with normal or corrected-to-normal Snellen visual acuity. All were unpracticed psychophysical observers with no prior exposure to the face stimuli and who were naïve with respect to the experimental hypotheses. Younger adults were undergraduates from McMaster University, and provided either $10/hr cash or course credit as compensation. Older adults were recruited from the local community and paid $10 per hour. Older adults were screened for visual pathologies with a vision and general health questionnaire, and cognitive impairments were assessed with the Mini Mental State Examination (Folstein et al., 1975) and Montreal Cognitive Assessment (Nasreddine et al., 2005). The experimental protocol was approved by the McMaster Research Ethics Board and written informed consent was obtained prior to participation. None of the subjects had participated in Experiment 1.

4.4.1.2 Apparatus & Stimuli

The apparatus was the same as in Experiment 1. The stimuli were digital photographs of three male and three female Caucasian models with no visible piercings, facial hair, or glasses. Photographs were taken as models rotated their head to fixate points located behind the photographer that were separated by 4.5° visual angle. Each model was represented by several diagonal viewpoints to the left and right, as well as one frontal viewpoint (refer to Gaspar et al. (2008) for additional details about the stimuli).

For the current experiment, two diagonal viewpoints were selected, one to the left and one to the right, that were of approximately equal eccentricity. Thus, each model used in the experiment had three possible viewpoints: front, left, or right. Six of the original 10 identities were selected based on which set of six produced averages with the fewest artifacts. Next, each face was centred in a 256 × 256 pixel matrix (8.6° × 8.6° visual angle) and cropped using a 256 × 190 pixel oval window to obscure external features such as hair, ears, and chin. The amplitude spectrum of each individual face was replaced with the average amplitude spectrum of the six faces from its corresponding viewpoint prior to image filtering. Stimulus contrast prior to the addition of white noise was 0.2 RMS. Sample faces from the various filter and bandwidth conditions are shown in Figure 4.8.



(a) 45° (Narrow) bandwidth condition **(b)** 90° (Wide) bandwidth condition

Figure 4.8 – Examples of stimuli used in Experiment 2. The top rows in each panel show target faces filtered to retain orientation structure centred on 0° (horizontal) or 90° (vertical) in the narrow (45°) bandwidth (a) and wide (90°) bandwidth (b) conditions. The experiment also used unfiltered stimuli and stimuli filtered to retain structure at ±45° (not shown). Context Absent stimuli are simply the orientation filtered target face (top rows in each panel). Context Present (bottom rows in each panel) stimuli are the pixelwise addition of the orientation filtered target (Context Absent) and orthogonal orientation structure from the average of all 6 faces (middle rows in each panel). Example stimuli from the left lateral and central viewpoints are shown in (a) and (b) respectively.

4.4.1.3 Procedure & Design

The procedure was the same as that used in the previous experiments, with the exception that faces could be either a frontal (same) or left/right lateral (different) viewpoint. Viewpoint was manipulated within-subjects and block order was counterbalanced across subjects. On each trial in the different viewpoint block, one of the two directions (right or left) was randomly selected for presentation. Faces on the response screen were always shown from a frontal viewpoint. Several parameters differed slightly between the two bandwidth conditions,[3] though the procedure itself was the same. In the wide bandwidth condition, observers performed a total of 1000 trials (100 trials per filter condition × 2 viewpoints), fixation duration was 500 ms, and there were 10 practice trials, whereas in the narrow bandwidth condition there were 800 trials (80 trials per filter condition × 2 viewpoints), the fixation duration was 250 ms, and there were 5 practice trials. All other details about the design and statistical analyses were identical to Experiment 1.

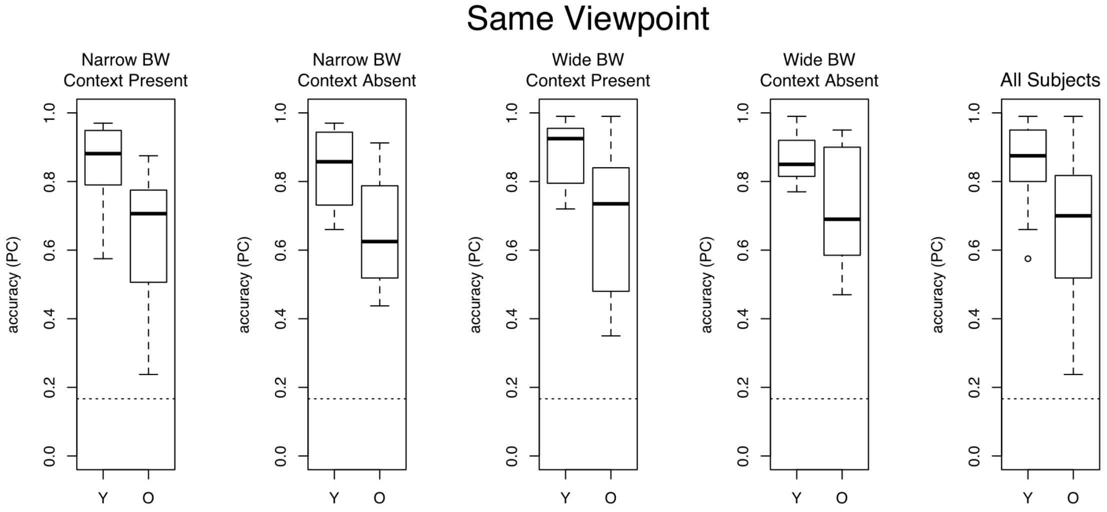


Figure 4.9 – Response accuracy for unfiltered, same viewpoint faces in Experiment 2. The rightmost plot shows data from all subjects, and the other four plots show accuracy measured for different groups of younger (Y) and older (O) participants who were assigned to the various filtered stimuli conditions. The horizontal dashed line in each plot indicates chance performance. Median response accuracy was consistently lower in older than younger participants.

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[3] These changes were made to make the length of the experiment more manageable for older adults.

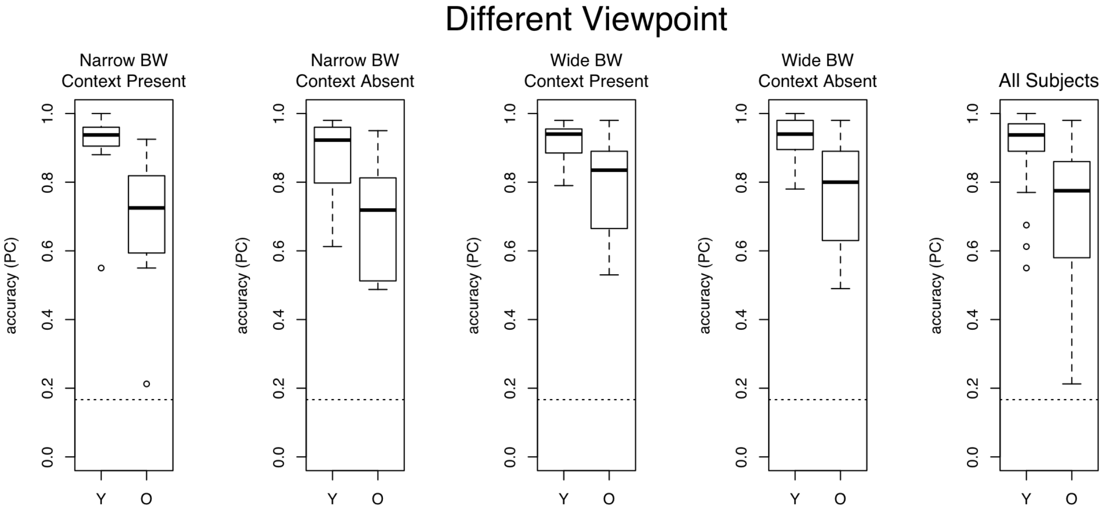


Figure 4.10 – Response accuracy for unfiltered, different viewpoint faces in Experiment 2. Plotting conventions are the same as in Figure 4.9. Median response accuracy was consistently lower in older than younger participants.

4.4.2 Results

4.4.2.1 Identification of Unfiltered Faces

Response accuracy in the unfiltered face condition in each of the eight groups at each viewpoint is shown in Figures 4.9 & 4.10. In the same viewpoint condition (Figure 4.9), average response accuracy was 0.86 (range = $[0.84, 0.88]$) in younger adults and 0.67 (range = $[0.64, 0.72]$) in older adults. In the different viewpoint condition (Figure 4.10), average response accuracy was 0.91 (range = $[0.87, 0.93]$) in younger adults and 0.74 (range = $[0.69, 0.79]$) in older adults. To see whether accuracy for unfiltered faces varied across conditions, we analyzed the data in Figures 4.9 & 4.10 with a 2 (Age Group) × 2 (Bandwidth) × 2 (Context) × 2 (Viewpoint) ANOVA. The results showed significant main effects of Age ($F(1, 88) = 42.67$, $\eta_p^2 = 0.33$, $p < .0001$) and Viewpoint ($F(1, 88) = 22.49$, $\eta_p^2 = 0.20$, $p < .0001$). The main effects of Bandwidth and Context were not significant, nor were any of the interactions ($F \leq 3.18$, $\eta_p^2 \leq 0.3$, $p \geq .08$ in each case). Thus, as in Experiment 1, we found that identification of unfiltered faces was significantly less accurate in older than younger adults. We also found higher response accuracy for faces that varied in viewpoint.

4.4.2.2 Orientation Filtered Faces

Figures 4.11 and 4.12 plot the accuracy data for filtered faces in the same viewpoint condition. Data for filtered faces in the different viewpoint condition are plotted in Figures 4.13 and 4.14. As was the case in Experiment 1, accuracy tended to be higher for younger than older adults. In both age groups, accuracy was highest in the horizontal filter condition compared to the obliques and vertical filter orientations, and this effect of filter orientation was greater in younger than older adults. Unsurprisingly, observers were more accurate as bandwidth increased, although this was most evident for the oblique orientations: With narrow bandwidth filters, accuracy in the oblique and vertical filter conditions was similar, but with wide bandwidth filters, accuracy in the oblique conditions was in-between accuracy in the vertical and horizontal conditions. Finally, this interaction between filter bandwidth and filter orientation was more pronounced for younger than older adults.

The data in Figures 4.11 through 4.14 were analyzed with a 2 (Age) × 4 (Filter Orientation) × 2 (Context) × 2 (Bandwidth) × 2 (Viewpoint) mixed ANOVA (see Table 4.2). The main effects of Age, Bandwidth, Context, Viewpoint, and Filter Orientation were significant; however, these effects were qualified by a significant three-way interaction between Age, Bandwidth, and Filter Orientation, and a significant four-way interaction between Bandwidth, Context, Filter Orientation, and Viewpoint.

To assess the Bandwidth × Context × Filter Orientation × Viewpoint interaction we averaged the data across age groups and analyzed accuracy in the narrow and wide bandwidth conditions with separate 2 (Context) × 4 (Filter Orientation) × 2 (Viewpoint) ANOVAs. In the narrow bandwidth condition, accuracy was significantly higher in the context absent ($M = 0.40$) than the context present ($M = 0.34$) condition ($F(1, 46) = 5.86$, $\eta_p^2 = .11$, $p = .02$), but the two- and three-way interactions with Context were not significant ($F \leq 1.80$, $\eta_p^2 \leq .04$, $p \geq .16$). The main effects of Filter Orientation ($F(1.69, 77.79) = 165.25$, $\eta_p^2 = .78$, $p < .0001$) and Viewpoint ($F(1, 46) = 5.66$, $\eta_p^2 = .11$, $p = .02$) and the Filter Orientation × Viewpoint interaction ($F(2.46, 112.99) = 8.48$, $\eta_p^2 = .16$, $p = .0001$) also were significant. Accuracy was slightly higher in the different viewpoint condition than the same viewpoint condition at the horizontal filter orientation ($t(94) = 2.33$, $d = 0.48$, $p = .022$), but the effect of viewpoint was not significant at the other filter orientations ($t \leq 1.60$, $d \leq 0.33$, $p \geq .112$).

For the wide bandwidth condition, the significant main effects of Filter Orientation

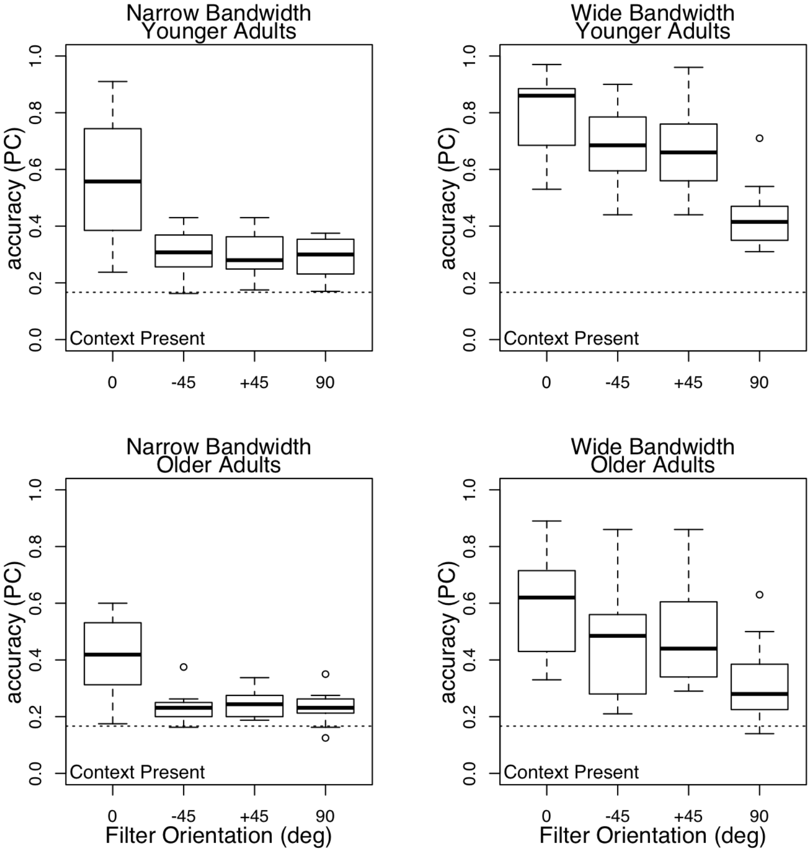


Figure 4.11 – Boxplots illustrating the distribution of response accuracy in Experiment 2 for filtered faces for younger (top row) and older adults (bottom row) in the Same Viewpoint Context Present condition. Results obtained with narrow and wide orientation bandwidths are shown in the left and right columns, respectively. Each panel shows accuracy for four filter orientations.

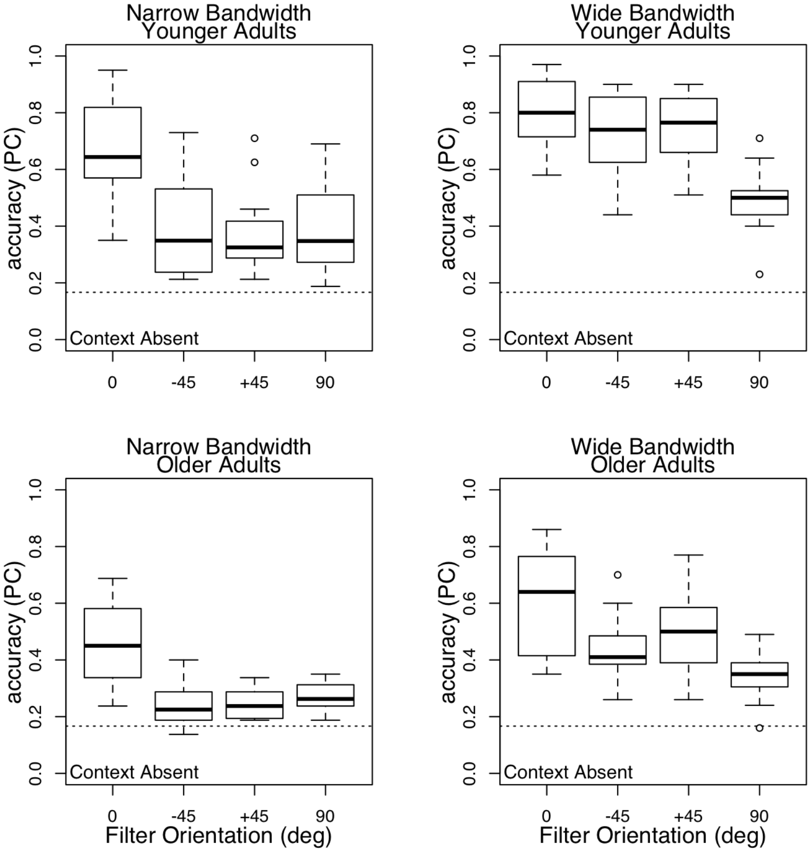


Figure 4.12 – Boxplots illustrating the distribution of response accuracy in Experiment 2 for filtered faces for younger (top row) and older adults (bottom row) in the Same Viewpoint Context Absent condition. Results obtained with narrow and wide orientation bandwidths are shown in the left and right columns, respectively. Each panel shows accuracy for four filter orientations.

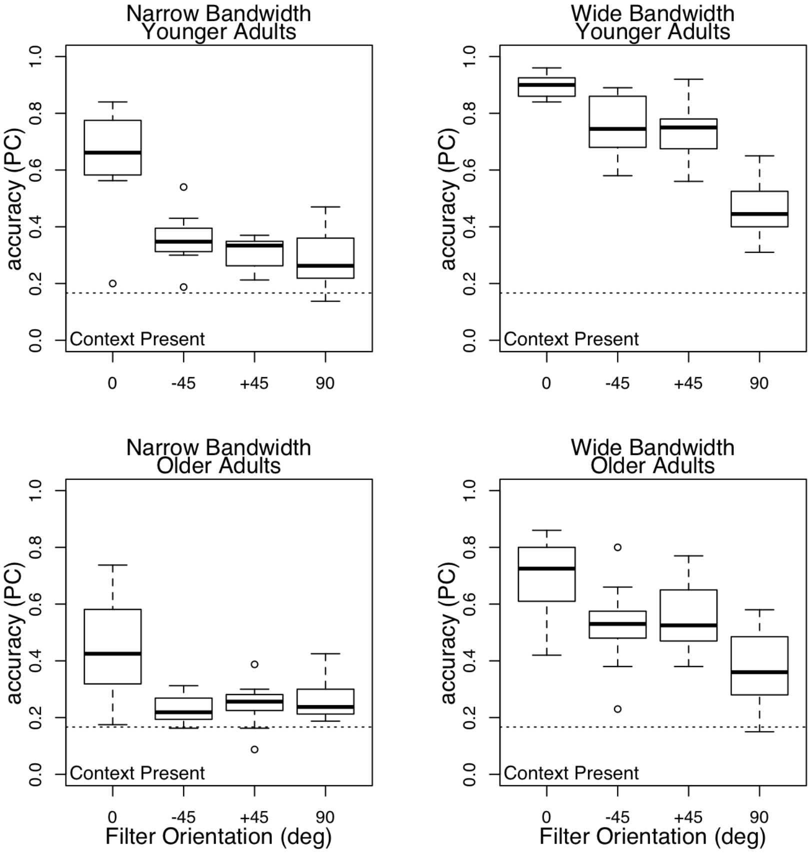


Figure 4.13 – Boxplots illustrating the distribution of response accuracy in Experiment 2 for filtered faces for younger (top row) and older adults (bottom row) in the Different Viewpoint Context Present condition. Results obtained with narrow and wide orientation bandwidths are shown in the left and right columns, respectively. Each panel shows accuracy for four filter orientations.

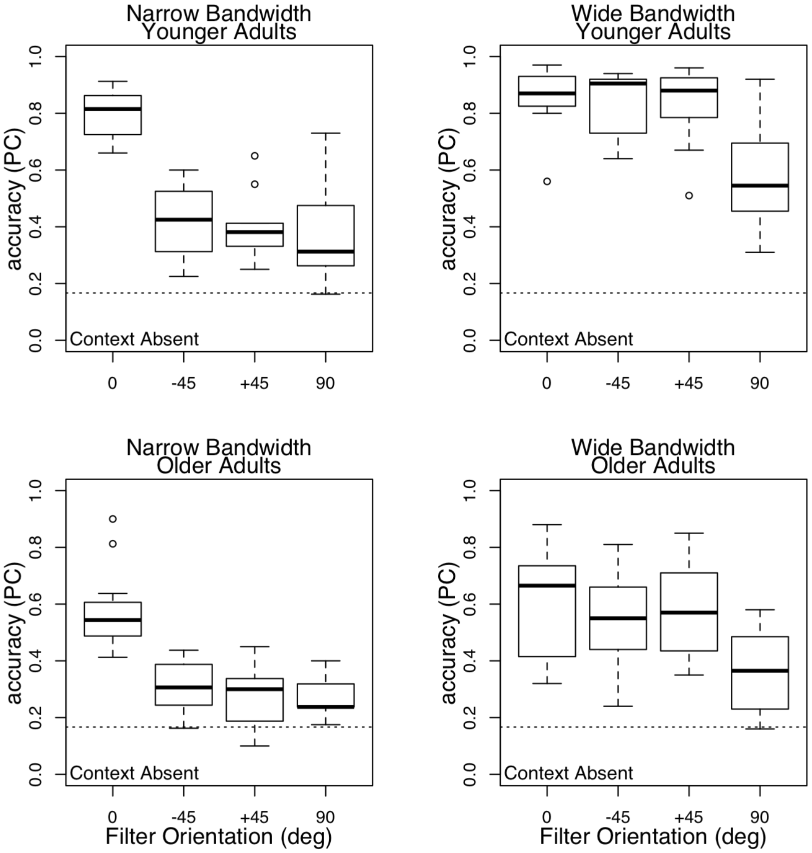


Figure 4.14 – Boxplots illustrating the distribution of response accuracy in Experiment 2 for filtered faces for younger (top row) and older adults (bottom row) in the Different Viewpoint Context Absent condition. Results obtained with narrow and wide orientation bandwidths are shown in the left and right columns, respectively. Each panel shows accuracy for four filter orientations.

Table 4.2 – Results from the Age (A) × Filter Orientation (FO) × Context (C) × Bandwidth (B) × Viewpoint (V) ANOVA on proportion correct data from Experiment 2.

Effect	**df**	**MSE**	F	η_p^2	p
A	1, 88	0.06	80.17	.48	<.0001
B	1, 88	0.06	159.84	.64	<.0001
C	1, 88	0.06	6.52	.07	.01
V	1, 88	0.03	20.22	.19	<.0001
A × B	1, 88	0.06	5.79	.06	.02
A × C	1, 88	0.06	2.39	.03	.13
B × C	1, 88	0.06	1.21	.01	.27
A × B × C	1, 88	0.06	0.02	.0003	.88
A × V	1, 88	0.03	0.14	.002	.71
B × V	1, 88	0.03	1.73	.02	.19
C × V	1, 88	0.03	0.31	.003	.58
A × B × V	1, 88	0.03	0.05	.0005	.83
A × C × V	1, 88	0.03	0.02	.0002	.90
B × C × V	1, 88	0.03	0.37	.004	.54
A × B × C × V	1, 88	0.03	0.48	.005	.49
FO	2.13, 187.34	0.01	311.76	.78	<.0001
A × FO	2.13, 187.34	0.01	9.44	.10	<.0001
B × FO	2.13, 187.34	0.01	61.67	.41	<.0001
C × FO	2.13, 187.34	0.01	0.50	.006	.62
A × B × FO	2.13, 187.34	0.01	4.63	.05	.009
A × C × FO	2.13, 187.34	0.01	0.52	.006	.61
B × C × FO	2.13, 187.34	0.01	4.67	.05	.009
A × B × C × FO	2.13, 187.34	0.01	0.12	.001	.90
FO × V	2.77, 243.60	0.00	5.80	.06	.001
A × FO × V	2.77, 243.60	0.00	0.51	.006	.66
B × FO × V	2.77, 243.60	0.00	4.09	.04	.009
C × FO × V	2.77, 243.60	0.00	0.56	.006	.63
A × B × FO × V	2.77, 243.60	0.00	0.25	.003	.85
A × C × FO × V	2.77, 243.60	0.00	1.39	.02	.25
B × C × FO × V	2.77, 243.60	0.00	4.44	.05	.006
A × B × C × FO × V	2.77, 243.60	0.00	0.09	.001	.96

($F(2.51, 115.27) = 169.41$, $\eta_p^2 = .79$, $p < .0001$), Viewpoint ($F(1, 46) = 16.34$, $\eta_p^2 = .26$, $p = .0002$), and the Context × Filter Orientation interaction ($F(2.51, 115.27) = 3.71$, $\eta_p^2 = .07$, $p = .02$) were qualified by a significant three-way interaction of Context, Filter Orientation, and Viewpoint ($F(2.62, 120.56) = 3.27$, $\eta_p^2 = .07$, $p = .03$). The other main effects and interactions were not significant ($F \leq 1.78$, $\eta_p^2 \leq .04$, $p \geq .16$). We analyzed the Context × Filter Orientation × Viewpoint interaction by conducting separate 2 (Context) × 2 (Filter Orientation) ANOVAs on the data from the same and different viewpoint conditions. For the same viewpoint condition, response accuracy was highest at the horizontal filter orientation ($M = 0.70$), intermediate for the left ($M = 0.58$) and right ($M = 0.60$) obliques, and lowest in the vertical ($M = 0.39$) condition, supporting the main effect of Filter Orientation ($F(2.61, 119.91) = 114.24$, $\eta_p^2 = .71$, $p < .0001$). Neither the main effect of Context ($F(1, 46) = 0.34$, $\eta_p^2 = .007$, $p = .56$) nor the Context × Filter Orientation interaction ($F(2.61, 119.91) = 0.82$, $\eta_p^2 = .02$, $p = .47$) was significant. The ANOVA on the different viewpoint condition indicated a significant main effect of Filter Orientation ($F(2.74, 126.08) = 119.31$, $\eta_p^2 = .72$, $p < .0001$) and significant Context × Filter Orientation interaction ($F(2.74, 126.08) = 5.96$, $\eta_p^2 = .11$, $p = .001$). The main effect of Context was not significant ($F(1, 46) = 0.34$, $\eta_p^2 = .007$, $p = .57$). Similar to the same viewpoint condition, accuracy was highest in the horizontal condition ($M = 0.76$), intermediate in the left ($M = 0.66$) and right ($M = 0.68$) oblique conditions, and lowest in the vertical ($M = 0.44$) condition. Response accuracy was numerically slightly higher in the context absent ($M = 0.65$) than context present ($M = 0.62$) condition, but the significant two-way interaction suggests the magnitude and/or direction of this difference varied with filter orientation. For the horizontal filter condition, the effect of context was in the opposite direction (i.e., performance was higher for context present than absent, $M = -0.07$) to the other filter orientations, however, this effect was small in all cases ($M = 0.02$, range $=$ [-0.07, 0.06]), and none of the follow-up comparisons were significant ($t \leq 1.34$, $d \leq 0.39$, $p \geq .19$ in each case).

To summarize, response accuracy was consistently highest for the horizontal filter orientation, intermediate for the obliques, and lowest for vertically filtered faces. In the narrow bandwidth condition, accuracy was slightly higher in the context absent than context present condition. Also, the overall effect of viewpoint was small ($M = 0.038$, range=[0.006, 0.09]) and statistically significant only for the horizontal filter orientation, where we found that accuracy was higher in the different viewpoint condition. In the wide bandwidth condition, accuracy in the context present and absent conditions was similar at all filter orientations in both the same and different viewpoint conditions.

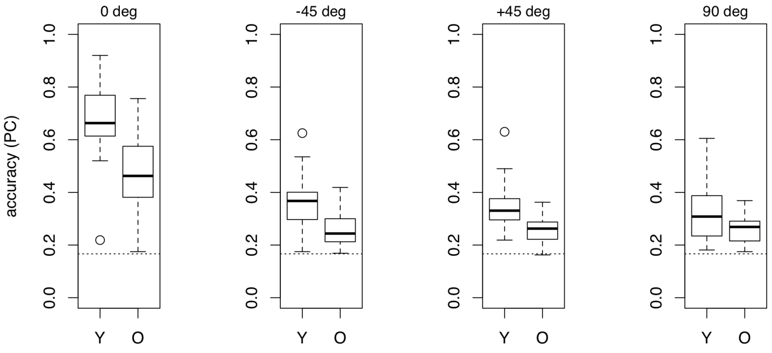
To facilitate a comparison to the results obtained in Experiment 1 which used only same viewpoint faces, we also assessed the Bandwidth × Context × Filter Orientation × Viewpoint interaction by analyzing accuracy in the same and different viewpoint conditions with separate 2 (Bandwidth) × 2 (Context) × 4 (Filter Orientation) ANOVAs. The ANOVA on the same viewpoint condition found no significant main effect of Context ($F(1, 92) = 1.92$, $\eta_p^2 = .02$, $p = .17$), or significant two- and three-way interactions involving Context ($F \leq 0.69$, $\eta_p^2 \leq .007$, $p \geq .52$ in each case). The main effect of Bandwidth ($F(1, 92) = 55.68$, $\eta_p^2 = .38$, $p < .0001$) and of Filter Orientation

($F(2.19, 201.55) = 182.38$, $\eta_p^2 = .66$, $p < .0001$) were significant. Response accuracy was highest in the horizontal filter orientation condition ($M = 0.61$), intermediate in the left ($M = 0.43$) and right ($M = 0.45$) obliques, and lowest for the vertical ($M = 0.34$) filter orientation, and was higher for the wide ($M = 0.57$, range=$[0.39, 0.70]$) than narrow ($M = 0.35$, range=$[0.29, 0.53]$) bandwidth condition. The effect of bandwidth was in the same direction at all filter orientations but varied in magnitude, as indicated by the significant Bandwidth × Filter Orientation interaction ($F(2.19, 201.55) = 34.95$, $\eta_p^2 = .28$, $p < .0001$). This difference ($M = 0.22$, range=$[0.10, 0.30]$) was significant at all filter orientations, being largest at the right ($t(75) = 10.07$, $d = 2.05$, $p < .0001$) and left ($t(78.06) = 8.57$, $d = 1.75$, $p < .0001$) obliques, intermediate for horizontal ($t(93.86) = 4.35$, $d = 0.89$, $p < .0001$), and smallest for the vertical filter orientation ($t(90.08) = 4.12$, $d = 0.84$, $p < .0001$). These results are consistent with our findings from Experiment 1: accuracy was greater in the wide than narrow bandwidth condition, and greatest in the horizontal and smallest in the vertical filter orientation conditions, and the effect of context on bandwidth did not vary systematically with filter orientation. In the different viewpoint condition, the main effects of Bandwidth ($F(1, 92) = 83.74$, $\eta_p^2 = .48$, $p < .0001$), Filter Orientation ($F(2.46, 226.02) = 209.88$, $\eta_p^2 = .70$, $p < .0001$), and the Bandwidth × Filter Orientation interaction ($F(2.46, 226.02) = 44.05$, $\eta_p^2 = .32$, $p < .0001$) were significant. However, these effects were qualified by a significant three-way interaction of Bandwidth, Context, and Filter Orientation ($F(2.46, 226.02) = 7.19$, $\eta_p^2 = .07$, $p = .0004$). The other main effects and interactions were not statistically significant ($F \leq 3.91$, $\eta_p^2 \leq .04$, $p \geq .05$). We analyzed the Bandwidth × Context × Filter Orientation interaction by conducting separate 2 (Bandwidth) × 2 (Context) ANOVAs on the data for each filter orientation. The main effect of Bandwidth was significant at each filter orientation ($F \geq 15.78$, $\eta_p^2 \geq .15$, $p \leq .0001$). The main effect of Context was small ($M = 0.05$, range = $[0.03, 0.06]$), and significant only for the right oblique ($F(1, 92) = 4.49$, $\eta_p^2 = .05$, $p = .04$) and vertical ($F(1, 92) = 4.18$, $\eta_p^2 = .04$, $p = .04$) filter orientations, but not the horizontal ($F(1, 92) = 0.90$, $\eta_p^2 = .01$, $p = .34$) or left oblique ($F(1, 92) = 3.70$, $\eta_p^2 = .04$, $p = .06$) conditions. Response accuracy tended to be higher in the wide ($M = 0.63$) compared to narrow ($M = 0.39$) bandwidth condition, and higher in the context absent ($M = 0.54$, range = $[0.40, 0.71]$) than the context present ($M = 0.49$, range = $[0.34, 0.67]$) condition. However, we found that the direction of the bandwidth effect varied with context in the horizontal ($F(1, 92) = 7.64$, $\eta_p^2 = .08$, $p = .007$) condition – accuracy was significantly higher in the context present condition when bandwidth was wide, but it was higher in the context absent condition when bandwidth was narrow – but not in the other filter orientation conditions (in each case, $F \leq 0.19$, $\eta_p^2 < .0001$, $p \geq .67$).

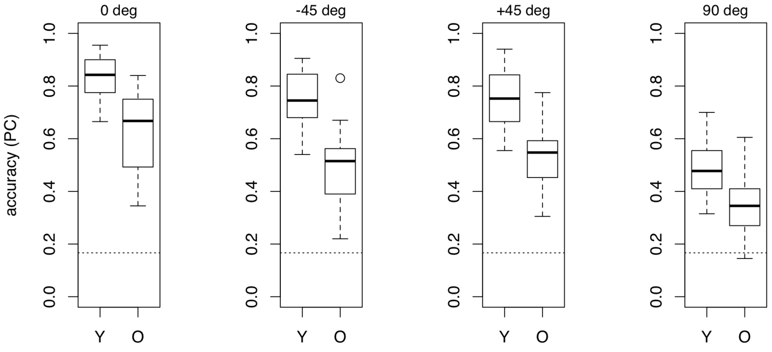
To summarize, response accuracy was consistently highest for the horizontal filter orientation, intermediate for the obliques, and lowest for vertically filtered faces. In the same viewpoint condition, accuracy was higher in the wide than narrow bandwidth condition, and this difference was most pronounced for the left and right oblique filter orientations. In the different viewpoint condition, the direction of this bandwidth effect varied with context and filter orientation: accuracy was higher in the context present than context absent condition for horizontally filtered faces, but approximately equal across context conditions at the other three filter orientations.

The ANOVA on accuracy for filtered faces also found a significant interaction between Age, Bandwidth, and Filter Orientation (Table 4.2). This interaction is shown in Figure 4.15, which plots the distribution of response accuracy in younger and older adults, averaged across the context and viewpoint conditions, for each filter orientation in the narrow and wide bandwidth conditions. A 2 (Age Group) × 4 (Filter Orientation) ANOVA on the data from the narrow bandwidth condition found significant main effects for Age ($F(1, 46) = 26.24$, $\eta_p^2 = .36$, $p < .0001$), Filter Orientation ($F(1.85, 84.89) = 191.26$, $\eta_p^2 = .81$, $p < .0001$), and a significant Age × Filter Orientation ($F(1.85, 84.89) = 8.43$, $\eta_p^2 = .15$, $p < .001$). The magnitude of the age effect varied across filter condition, being largest for horizontal ($t(45.81) = 4.97$, $d = 1.44$, $p < .0001$), intermediate at the left ($t(38.35) = 5.00$, $d = 1.43$, $p < .0001$) and right ($t(38.25) = 4.14$, $d = 1.19$, $p < .0001$) oblique orientations, and smallest for vertically filtered faces ($t(31.27) = 2.78$, $d = 0.80$, $p = .009$). In the wide bandwidth condition, the ANOVA found significant main effects of Age ($F(1, 46) = 49.01$, $\eta_p^2 = .52$, $p < .0001$) and Filter Orientation ($F(2.31, 106.43) = 175.22$, $\eta_p^2 = .79$, $p < .0001$). Followup tests on the significant Age × Filter Orientation interaction ($F(2.31, 106.43) = 5.41$, $\eta_p^2 = .11$, $p = .004$) showed that the magnitude of the age difference was greatest in the left oblique condition ($t(43.98) = 7.14$, $d = 2.06$, $p < .0001$), intermediate and approximately equal for the horizontal ($t(35.35) = 5.80$, $d = 1.67$, $p < .0001$) and right oblique ($t(46) = 6.52$, $d = 1.88$, $p < .0001$) conditions, and smallest in the vertical condition ($t(45.95) = 4.67$, $d = 1.35$, $p < .0001$). We also conducted separate 2 (Age Group) × 2 (Bandwidth) ANOVAs for each filter orientation. In each case, there were significant main effects of Age ($F \geq 28.77$, $\eta_p^2 \geq .24$, $p \leq .0001$) and Bandwidth

($F \geq 33.01$, $\eta_p^2 \geq .26$, $p \leq .0001$). The Age × Bandwidth interaction was significant for both the left ($F(1, 92) = 11.05$, $\eta_p^2 = .11$, $p = .001$) and right ($F(1, 92) = 10.16$, $\eta_p^2 = .10$, $p = .002$) oblique filter orientations, where the age difference was larger in the wide bandwidth condition, but was not significant for the horizontal ($F(1, 92) = 0.04$, $\eta_p^2 = .0005$, $p = .84$) and vertical ($F(1, 92) = 3.15$, $\eta_p^2 = .03$, $p = .08$) filter conditions. Thus, we found that face identification accuracy was lower in older adults at all filter orientations in both the narrow and wide bandwidth conditions, and that the size of this age difference varied with filter orientation at both bandwidths, but in different ways: in the wide bandwidth condition the age difference was largest for the left oblique filter orientation, whereas in the narrow bandwidth condition the age difference was largest for horizontally filtered faces.



(a) Narrow Bandwidth



(b) Wide Bandwidth

Figure 4.15 – Boxplots illustrating the Age × Filter Orientation × Bandwidth interaction found in Experiment 2 (see Table 4.2). Each plot depicts the distributions of response accuracy in younger (Y) and older (O) adults for one filter orientation after averaging data across context and viewpoint conditions. Data from the narrow and wide conditions are shown in the top and bottom rows, respectively. The group difference was statistically significant in every case.

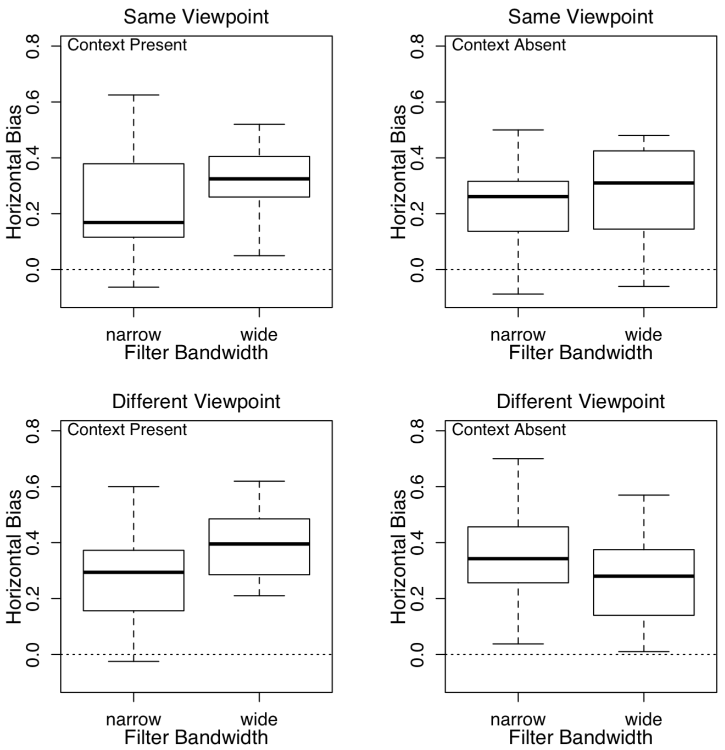
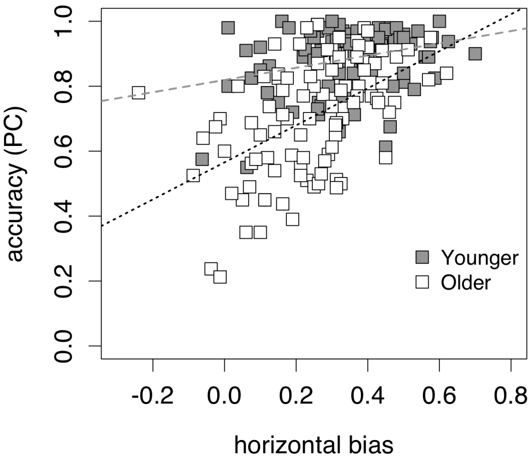


Figure 4.16 – Boxplots of horizontal bias measured in Experiment 2 for the Same and Different viewpoint conditions in the Context Present and Absent conditions at each level of Filter Bandwidth, after combining data from younger and older observers. Horizontal bias was defined as difference between accuracy in the horizontal and vertical filter conditions.

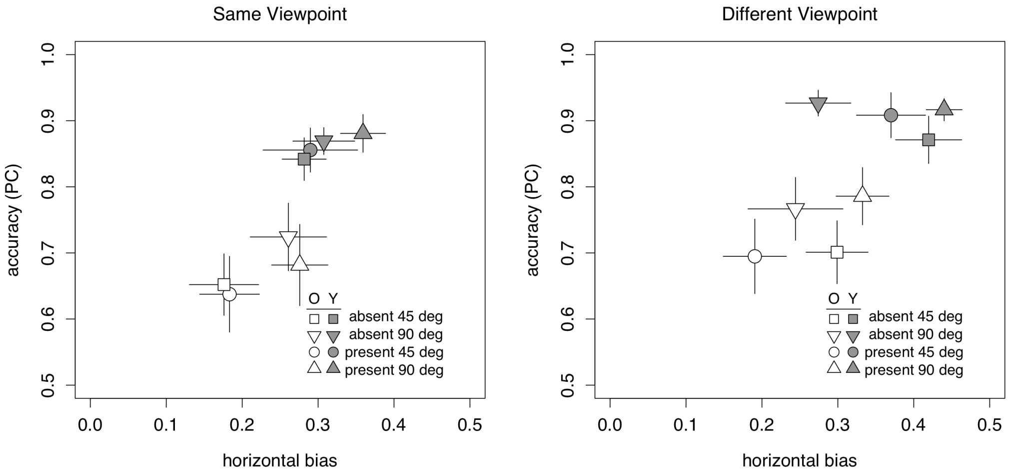
4.4.2.3 Identification vs. Horizontal Bias

We analyzed horizontal bias scores with a 2 (Age Group) × 2 (Context) × 2 (Bandwidth) × 2 (Viewpoint) ANOVA. The grand mean of the horizontal bias scores differed significantly from zero ($F(1,88) = 515.16$, $\eta_p^2 = .85$, $p < .0001$). The main effect of Viewpoint was significant ($F(1,88) = 11.59$, $\eta_p^2 = .12$, $p = .001$) because horizontal bias was higher in the different viewpoint condition ($M = 0.32$) than same viewpoint condition ($M = 0.27$). Older adults demonstrated a significantly smaller horizontal bias ($M = 0.25$) compared to younger adults ($M = 0.34$), as indicated by the significant main effect of Age ($F(1,88) = 14.15$, $\eta_p^2 = .14$, $p = .0003$). The ANOVA on horizontal bias also yielded significant two-way interactions of Context × Bandwidth ($F(1,88) = 5.00$, $\eta_p^2 = .05$, $p = .03$) and Bandwidth × Viewpoint ($F(1,88) = 4.15$, $\eta_p^2 = .05$, $p = .04$) that were qualified by a significant three-way interaction of Context, Bandwidth, and Viewpoint ($F(1,88) = 7.95$, $\eta_p^2 = .08$, $p = .006$). This three-way interaction is depicted in Figure 4.16: the median horizontal bias was greater with wide bandwidth filters than narrow bandwidth filters in all conditions except in the context-absent, different-viewpoint condition. We explored this interaction by conducting separate 2 (Context) × 2 (Bandwidth) ANOVAs for the horizontal bias data in the same and different viewpoint conditions. For the same viewpoint condition (shown in the top row of Figure 4.16), horizontal bias was significantly higher at the wide ($M = 0.30$) than narrow ($M = 0.23$) bandwidth, as indicated by the significant main effect of Bandwidth ($F(1,92) = 4.79$, $\eta_p^2 = .05$, $p = .03$). The main effect of Context ($F(1,92) = 0.43$, $\eta_p^2 = .005$, $p = .51$) and the Context × Bandwidth interaction ($F(1,92) = 0.17$, $\eta_p^2 = .002$, $p = .68$) were not significant. The ANOVA on the different viewpoint condition (Figure 4.16, bottom row) yielded non-significant main effects of Context ($F(1,92) = 0.55$, $\eta_p^2 = .006$, $p = .46$) and Bandwidth ($F(1,92) = 0.01$, $\eta_p^2 < .0001$, $p = .93$); however, the direction of the effect of bandwidth varied with context. This significant Context × Bandwidth interaction ($F(1,92) = 10.09$, $\eta_p^2 = .10$, $p = .002$) reflected the fact that horizontal bias was significantly greater at the wide than narrow bandwidth in the context present condition ($t(39.86) = 2.49$, $d = 0.72$, $p = .017$), but significantly lower in the context absent condition ($t(44.90) = 2.04$, $d = 0.59$, $p = .047$). In summary, we found that horizontal bias was significantly lower in older adults than younger adults and that the age difference did not vary significantly across conditions. Experiment 2 also found horizontal bias was higher in the wide than narrow bandwidth condition for same viewpoint faces and for different viewpoint faces in the context present condition, but horizontal bias was higher in the narrow than wide bandwidth condition for context absent, different viewpoint faces. However it is important to note that the size of this bandwidth effect was small in all cases.

The scatter plot shown in Figure 4.17 illustrates the association between identification accuracy and horizontal bias for younger and older individuals. Because age differences in horizontal bias were constant across bandwidth, context, and viewpoint, we analyzed the data after averaging across these factors. The correlation between identification accuracy and horizontal bias was significantly greater than zero overall ($r = 0.48$, $t(190) = 7.63$, $p < .0001$, 1-tailed) and in both age groups (younger: $r = 0.21$, $t(94) = 2.10$, $p = .019$, 1-tailed; older: $r = 0.47$, $t(94) = 5.12$, $p < .0001$, 1-tailed). This positive association is seen more clearly in Figure 4.17 b &c, which plots mean identification accuracy and horizontal bias for each of the 8 groups in the same and different viewpoint conditions.



(a) Identification accuracy vs. horizontal bias.



(b) Group means (same viewpoint). **(c)** Group means (different viewpoint).

Figure 4.17 – Identification accuracy for unfiltered faces and horizontal bias measured in Experiment 2. a): Accuracy is plotted against horizontal bias for younger (grey) and older (white) observers. Each individual observer from each of the 4 possible Context (present/absent) and Bandwidth (narrow/wide) combinations is represented by two points, one for the same viewpoint condition and one for the different viewpoint condition. The dashed and dotted lines represent the least-squares regression lines fit to data from younger and older observers, respectively. b & c): Each point represents the mean identification accuracy and mean horizontal bias in one group for the same (b) and different (c) viewpoint conditions. Note that the vertical axes in (b) & (c) start at 0.5, not 0. Error bars represent ±1 SEM.

4.4.3 Discussion

Consistent with Experiment 1, we found younger and older adults identified faces more accurately when filtered to retain horizontal structure compared to vertical structure. However, unlike Experiment 1, we found that the age difference in horizontal bias was not influenced by the presence of non-informative context: horizontal bias was lower in older adults both when informative facial structure was shown in isolation and within non-informative facial structure. We also found that, although older adults were less accurate at all filter orientations, the magnitude of the age effect was greatest for horizontal filter orientations at the narrow bandwidth and for the left oblique filter at the wider bandwidth.

Identification accuracy for unfiltered faces was positively associated with horizontal bias in both age groups, supporting the idea that group differences in horizontal bias contribute to group differences in face identification. However, as was found in Experiment 1, we found significant age differences in identification accuracy even in conditions in which the mean horizontal bias was similar in the two age groups. Hence, age differences in face identification accuracy were not due entirely to differences in horizontal bias. This point is seen most clearly by examining the group averages of identification accuracy and horizontal bias from Experiments 1 and 2 (see Figure 4.7 c & Figure 4.17 b & c).

4.5 General discussion

Previous studies have shown that face identification accuracy is lower in older adults (Searcy et al., 1999; Habak et al., 2008; Grady et al., 2000; Grady, 2002; Owsley et al., 1981; Konar et al., 2013), a finding that we replicated in this set of experiments. Here, we explored the possibility this age difference is due to less efficient processing of diagnostic horizontal facial structure. To that end, we compared the performance of younger and older adults on a 6-AFC identification task where faces were filtered to retain diagnostic structure centred on horizontal, oblique, or vertical orientations. We further examined how the age difference in identification depends on filter bandwidth and whether or not the orientation of the diagnostic information was known.

Consistent with previous research (Obermeyer et al., 2012; Goffaux et al., 2015; Yu and Chung, 2011), we found that older adults, like younger adults, weigh diagnostic horizontal information more heavily than vertical information when identifying faces. However, our results also suggest that older observers use horizontal facial structure less efficiently than younger observers. Across all our experimental manipulations, older adults performed more poorly than younger adults at all filter orientations, and the age difference tended to be most pronounced when the target face contained horizontal structure. These effects were particularly evident when the diagnostic horizontal structure was limited to a narrow band embedded amongst other non-informative orientation structure. Further, these experiments show for the first time that individual differences among older adults in horizontal bias are correlated with individual differences in face identification: In Experiment 2 and the context present condition of Experiment 1, the two measures were significantly positively correlated. However, our results suggest age differences in horizontal bias cannot account fully for age differences in face identification, because the magnitude of age-related declines in face identification were not reliably accompanied by an age-related decline in horizontal bias of similar magnitude. Thus, we found only partial support for the hypothesis that age-related declines in horizontal bias contribute to older adults' impaired face identification. It would be beneficial for future research to measure the association between horizontal bias and face identification to further substantiate the strength of this claim.

Naturalistic faces are broadband stimuli, and observers must extract task-relevant information and potentially suppress or ignore irrelevant context. One common criticism of filtering studies is that the resulting stimuli are less "face-like", which might cause observers to rely on a different strategy than they use when identifying everyday faces. To address this issue, Pachai et al. (2018) created face stimuli that contained structure at all orientations, but contained *informative* structure (i.e., target identity) only in a particular orientation band. We adopted that approach here, and also included a context absent condition, to allow a comparison to previous aging studies. One reason for including context is that face-specific mechanisms, such as holistic processing, may differ in older and younger adults (Adduri and Marotta, 2009; Chaby et al., 2011; Konar et al., 2013; Meinhardt-Injac et al., 2014). For example, a common measure of holistic processing is the Composite Face Effect (CFE), in which observers are slower and less accurate at discriminating the top half of a face when it is aligned with the task-irrelevant bottom half of the face than when the top and bottom are misaligned. That the task-irrelevant context (bottom halves) influences performance in the aligned condition is taken as evidence that humans unavoidably integrate information over the entire face. Konar et al. (2013) found the reaction times of older adults was more affected by this irrelevant context compared to younger adults, and that the CFE was correlated with face identification accuracy in older, but not younger, adults. These findings raise the possibility that the effects of face context on identification accuracy might differ in older and younger adults. The results of Experiment 1 support the idea that older adults' horizontal bias is more affected by non-informative facial context; however, using a different face set, in Experiment 2 we found that the effects of context on horizontal bias were similar in the two age groups. What is consistent across both experiments, however, is that context had no effect on horizontal bias in younger adults.

The current experiments used two orientation bandwidths that were relatively broad. The size of our narrow bandwidth condition (±22.5°, or 45° full width) is in line with previous aging studies (ranging between ±20° (Goffaux et al., 2015) and ±23° (Obermeyer et al., 2012; Yu and Chung, 2011; Schaich et al., 2016)), however we also included a wider bandwidth (±45°, or 90° full width). Nevertheless, our findings were consistent with the previous aging studies: older adults exhibited horizontal bias at both bandwidths tested. Though not statistically significant, age differences in horizontal bias tended to become less pronounced as bandwidth increased, suggesting older observers integrate orientation information over a broader range compared to younger adults when identifying faces. The bandwidths included in our experiment were chosen to span the bandwidth producing the greatest horizontal bias in younger observers in Pachai et al. (2018) (≈70°), but it remains possible that our results could be different had we used different bandwidths. An important next step in this line of research is to precisely characterize the tuning function of horizontal bias in older adults by parametrically varying filter bandwidth.

In summary, consistent with prior research, older adults were biased toward horizontal structure when identifying faces. With the exception of the Context Absent condition in Experiment 1, we observed an age-related decline in older adults' bias toward horizontal spatial frequency components relative to their younger counterparts. We show that horizontal bias is correlated with identification accuracy in older adults, however horizontal bias was unable to fully account for the age-related decline in face identification in all conditions.

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Chapter 5

General Discussion

The goal of this thesis was to characterize age-related changes in face perception using a biologically plausible, data-driven approach that is consistent with how signals are represented at early stages of visual processing. To that end, I used a variety of psychophysical techniques to measure classification images (Chapter 2), equivalent input noise (Chapter 3, Experiment 1), response consistency (Chapter 3, Experiment 2), and the effects of orientation filtering on identification (Chapter 4) to demonstrate that older adults' face discrimination and identification is constrained to a relatively greater degree by internal noise and decreased sampling efficiency compared to younger observers. Below, I summarize the results and contributions of my work, situate these findings within the broader research context, and suggest several avenues for further study.

5.1 Summary of Results

In Chapter 2 I used a variant of the response classification technique to examine how older and younger adults visually sample information when discriminating faces. Specifically, I used white visual noise to mask the information conveyed at various spatial locations on a face, and examined how noise at each spatial location affected an observer's decision. Using the noise fields for each stimulus-response class, I constructed a classification image (CI) for each observer and cross-correlated it with the visual template of a linear ideal observer to obtain an estimate of absolute efficiency. In line with previous research, the CIs from younger observers contained structure in the eye/brow region. However, the results differed qualitatively in older observers: the CIs from a few observers contained structure in the eye/brow region and in relatively less informative regions such as the forehead and mouth, the CIs from most older observers showed no obvious spatial structure. Cross-session variability also was higher in older observers. These age differences in CIs suggest that younger and older observers differed in the degree to which face discrimination was driven by information conveyed by structure near the eyes and brows. Relative to younger adults, older adults had higher face discrimination thresholds and lower cross-correlations with the ideal template, indicating an age-related decline in sensitivity and absolute efficiency. Importantly, I demonstrated these two measures were strongly and similarly correlated in both age groups, suggesting that despite the lack of obvious structure, the classification image technique is able to characterize individual differences in older observers' perceptual strategy. These experiments were the first to use the response classification method to study age differences in judgements of face identity, although related techniques have been used to explore older observers' facial representations of trustworthiness (Éthier-Majcher et al., 2013), age (Van Rijsbergen et al., 2014), discrimination of emotions (Smith et al., 2018), and face detection (Jaworska et al., 2020).

Chapter 3 used the equivalent input noise and double-pass response consistency paradigms to test whether older observers' lack of apparent structure in their CIs, lower cross-correlation with the ideal template, and increased inter-session variability reflects an age-related increase in internal noise. In Experiment 1, I measured threshold-vs.-noise (TvN) curves for each observer in order to extract the parameters representing equivalent input noise and high-noise efficiency. I found older observers had higher equivalent input noise and lower high-noise efficiency compared to younger observers, a result suggesting older observers' face discrimination is limited by both increased additive internal noise and decreased calculation efficiency. In Experiment 2, I measured the covariance between percent correct and percent agreement across two passes of identical signal+noise arrays in order to determine each observer's internal-to-external (I/E) noise ratio. The I/E ratios were similar in the two age groups, suggesting the age difference in high-noise efficiency found for Experiment 1 is due primarily to decreased calculation efficiency rather than increased multiplicative internal noise. Importantly, this last finding indicates age differences in the spatial structure in CIs found in Chapter 2 reflect an age-related decline in efficiency of information use. Together, these studies are the first to demonstrate the relative contributions of internal noise and calculation efficiency to older adults' ability to discriminate facial identity.

Finally, in Chapter 4, I examined age-related changes in the selective use of orientation facial structure. To my knowledge these experiments are the first to test whether age-related changes in horizontal bias are associated with face identification accuracy. Specifically, I measured identification performance for faces filtered to retain information in bands centred around horizontal (0°), vertical (90°), and oblique (±45°) orientations, and varied target bandwidth (either 45° or 90°) to examine the range over which younger and older observers extract and integrate orientation structure. Target information was either presented by itself or embedded within a non-informative facial context. This latter condition created faces that contained structure at all orientations and thus ought to engage normal face processing mechanisms, but diagnostic information was present only within a given band. Both younger and older adults relied more heavily on horizontal structure compared to other orientations, and older adults had poorer identification accuracy both for unfiltered and orientation filtered faces. In Experiment 1, age-related decreases in horizontal bias only were observed in the presence of non-informative orientation structure, and these bias scores were positively associated with face identification accuracy in only older adults. In Experiment 2, horizontal bias was smaller for older than younger adults regardless of context, and positively associated with face identification in both age groups. Although horizontal bias and face identification accuracy are positively associated in older adults, age-related deficits in face identification can only be partly explained by older adults' weaker reliance on horizontal facial structure.

5.2 Implications

Much of my thesis research was motivated by neurophysiological and psychophysical work suggesting age-related changes in internal noise and/or calculation efficiency may contribute to age-related changes in low-level visual perception. For example, single-cell recordings in senescent non-human animals suggest visual cortical neurons sensitive to spatial frequency, orientation, and direction of motion exhibit increased spontaneous and visually-evoked activity, greater trial-to-trial response variability, and lower signal-to-noise ratios (Hua et al., 2006; Schmolesky et al., 2000; Yang et al., 2009; Yu et al., 2006). Higher internal noise in older than younger rhesus monkeys also may exist at the neural population coding level (Wang et al., 2019). Neurons sensitive to orientation and direction discrimination in cats (Hua et al., 2006) and rhesus monkeys (Schmolesky et al., 2000; Yu et al., 2006) also become more broadly tuned with increasing age, which can decrease sampling efficiency in some visual tasks. In humans, older observers have shown greater internal noise in psychophysical tasks such as motion detection, direction and orientation discrimination, and detection of sine wave gratings at high (10 cpd) spatial frequencies (Allard et al., 2013; Bennett et al., 2007; Betts et al., 2007; Bogfjellmo et al., 2013; Bower and Andersen, 2012; Pardhan, 2004). Calculation efficiency also declines with age on many visual perception tasks: grating detection at a range (1-9 cpd) of spatial frequencies (Bennett et al., 1999; Pardhan et al., 1996; Allard et al., 2013), motion discrimination at high speeds (Bogfjellmo et al., 2013), and vernier acuity (Li et al., 2012).

Thus, there is ample evidence from low-level vision illustrating the need to consider how *both* internal noise and efficiency contribute to visual aging. The output of low-level mechanisms such as orientation and spatial frequency selective channels are integrated in higher cortical areas to form representations of complex stimuli (e.g., faces), and this thesis is notable as the first to use response classification, equivalent input noise, and response consistency to assess the influence of both efficiency and internal noise on older adults' face discrimination. Often, age-related deficits in face perception are treated as arising from some form of information processing inefficiency (e.g., processing speed, spatial sampling, memory, changes in functional connectivity). My findings from Chapter 2 and Chapter 3 (Experiment 1) are consistent with an age-related decrease in calculation efficiency. Experiment 1 in Chapter 3 also provides evidence for an age-related increase in additive internal noise. Further, the effect of additive internal noise contributed more than calculation efficiency to older adults' increased face discrimination thresholds. Most aging studies of face discrimination measure performance in the absence of noise-masking, and therefore cannot assess whether these findings truly reflect age-related changes in information processing efficiency, rather than age-related changes in internal noise or age-related changes in the relative contribution of the two.

Knowledge that both calculation efficiency and additive internal noise constrain older adults' ability to discriminate and identify faces can help inform and extend prior findings in the literature. For example, horizontal structure that is diagnostic for facial identity is concentrated in the eye/brow region (Duncan et al., 2017; Gold et al., 1999; Gosselin and Schyns, 2001; Pachai et al., 2013a; Royer et al., 2018; Schyns et al., 2002; Sekuler et al., 2004), and lower calculation efficiency in older observers could be the due to decreased efficiency in using the eyes/brows and/or reliance on less diagnostic regions. Indeed, in Chapter 2 I show that older observers less consistently relied on pixels in the eye region, and also based their decisions on less informative spatial regions such as the forehead. Furthermore, in Chapter 4 I found older observers generally showed a reduced horizontal bias (although this could not entirely explain age-related changes in identification performance). The idea that age-related deficits in face processing may be due to the decreased efficiency with which older observers encode task-relevant information conveyed by the eye/brow region is consistent with prior eye-tracking studies (Chan et al., 2011; Firestone et al., 2007; Heisz and Ryan, 2011; Murphy and Isaacowitz, 2010; Sullivan et al., 2007; Wong et al., 2005). However, age differences in eye movements should be interpreted with caution because fixated positions might not always represent regions critical to the observer performing the task.

For example, Firestone et al. (2007) found that despite exhibiting *poorer* recognition memory, older adults made more eye movements between inner facial features (such as the eyes) compared to younger adults. Also, Chan et al. (2011) found that yoking older adults' eye-movements to those of younger observers (who are presumed to rely more on the eye/brow region) did not increase performance on an old/new recognition task, nor did yoking younger adults' eye-movements to those of older observers decrease performance. That is, neither increased spatial sampling of informative regions nor recapitulating the fixation patterns of younger observers improved older adults' performance. This result suggests that the eye-tracking method may not be adequately capturing older observers' decision process. Peterson and Eckstein (2012) showed that only a small number of fixations to a highly localized area are sufficient to support fast and accurate face identification. This result suggests that information from the periphery may also be encoded during each fixation, and it is possible older adults rely more heavily on peripheral vision to compensate for less efficient use of centrally fixated regions. The findings of Firestone et al. (2007) and Chan et al. (2011) might also result from higher internal noise in older relative to younger observers in these studies since processing more similar to those of younger observers failed to improve older adults' performance. Age differences in peripheral vision and additive internal noise might not manifest themselves as age differences in fixation patterns, but ought to show up as age differences in classification images. My work in Chapter 2 provides a measure of the relation between decisions in a face discrimination task and contrast at each stimulus pixel that is not dependent on fixation location. Although the CI technique is unable to directly quantify the influence of internal noise, stimuli were presented in conditions (i.e., high external noise) where additive internal noise contributes little to performance.

One important contribution of my work is showing that the response classification, equivalent input noise, and response consistency paradigms are able to adequately characterize the behaviour of older adults performing a face discrimination task. The data in this thesis are interpreted within the context of Pelli's early-noise Linear Amplifier Model (LAM; Pelli, 1981, 1990) for characterizing an observer's decision process. Like any model, the LAM has its limitations and is constrained by certain assumptions. The idea that the visual processing of an observer is linear obviously is an oversimplification. Nevertheless, the LAM adequately accounts for TvN curves measured in a wide range of tasks (Bennett et al., 1999; Gold et al., 2005; Legge et al., 1987; Pelli, 1981; Pelli and Farell, 1999; Tjan et al., 1995), including face perception in younger adults (Albonico et al., 2018; Christensen et al., 2013; Gaspar et al., 2008b; Gold et al., 1999, 2004; Shafai and Oruc, 2018). The methods used in Chapters 2 and 3 may not be sensitive to age differences in non-linear components of face processing such as holistic processing. Older adults' face processing may rely more on holistic processing (Adduri and Marotta, 2009; Daniel and Bentin, 2012; Konar et al., 2013; Meinhardt-Injac et al., 2014), even if it results in worse performance (Konar et al., 2013; Meinhardt-Injac et al., 2014). However, results in Chapter 2 and 3 are inconsistent with the idea that classification images are insensitive to age differences in face processing. In Chapter 2 I found that a measure of absolute efficiency (i.e., the cross-correlation between a classification image and the ideal template) was strongly ($r = -0.89$) and similarly correlated with face discrimination thresholds in *both* age groups ($r_Y = -0.74$, $r_O = -0.73$). Also, Chapter 3 found that the LAM provided good fits to the average noise-masking functions in both groups ($R^2_Y = .997$, $R^2_O = .989$). Hence, the LAM provides a good description of psychophysical performance in younger and older observers. Nevertheless, it is worth emphasizing that it would be incorrect to interpret my work as asserting that older (or younger) observers are linear. Further, my results cannot speak to whether any nonlinear processes operating in younger and older adults are the same in both groups. Finally, although these data are well fit by an early-noise LAM, my work does not preclude the possibility that alternative and/or more complex models can provide similar explanatory power, or explain additional, non-overlapping variance in older adults' face discrimination.

The LAM also assumes that calculation efficiency and the variance of the internal noise are independent of stimulus contrast; however, this may not always be the case (Allard and Cavanagh, 2012; Burgess and Colborne, 1988; Tolhurst et al., 1983). Recall that the slope of the noise-masking function, k, can be affected by both calculation efficiency and multiplicative internal noise. In Chapter 3 (Experiment 2) I measured this type of internal noise using the double-pass response consistency method (Burgess and Colborne, 1988; Green, 1964; Spiegel and Green, 1981) and found that multiplicative internal noise did not vary as a function of age. This rules out the contribution of contrast-dependent internal noise to older adults' face discrimination thresholds, which supports the conclusion that the age-related decrease in absolute efficiency found in Experiment 1 (Chapter 3) is due to an age-related decrease in calculation efficiency. Murray et al. (2005) showed mathematically that the signal-to-noise ratio (SNR) of an observer's CI is affected by both calculation efficiency and internal noise – observers with little internal noise (which could include either additive or multiplicative) and a high calculation efficiency will have higher SNRs and hence clearer structure in their CIs. The CI experiment in Chapter 2 always presented stimuli in high external noise variance, where additive internal noise does not significantly contribute (Burgess and Colborne, 1988). Therefore, the results of the response consistency experiment also rule out the the possibility that an age difference in multiplicative internal noise was a major contributor to the less obvious structure in older adults' CIs, the lower cross-correlation between older observers' CIs and the ideal linear discriminator, and the increased cross-session CI variability found in Chapter 2.

Allard and Cavanagh (2012) suggested that the strategy used by observers may depend on the spatial and temporal extents of the external noise relative to the target, and that using spatio-temporally extended noise (i.e., dynamic noise across the entire display) is more similar to the internal noise in the visual system. In other words, calculation efficiency may be noise-dependent, with observers relying on different strategies based on whether the dominant source of noise is internal (in low external noise conditions) or external (in high external noise conditions). Further, Allard et al. (2013) found that age differences in contrast sensitivity at low spatial frequencies were attributable to decreased calculation efficiency when stimuli were presented in local (over the stimulus) static external noise, but to increased equivalent input noise using extended (across the entire screen), dynamic noise. Experiment 1 in Chapter 3 only tested observers with local static noise, and it is possible my interpretation of the TvN curves would change had I used extended dynamic external noise.

Another commonly-used model for interpreting the results of threshold-vs.-noise experiments is the Perceptual Template Model (PTM; Dosher and Lu, 1999). One key difference between the LAM and PTM is the location of the internal noise within the observer. In the PTM, all of the internal noise (both contrast-independent and contrast-dependent) is placed *after* the calculation, rather than before (as in the LAM). In the LAM, the I/E ratio is unaffected by the calculation, whereas in the PTM the I/E ratio is (potentially) affected by the calculation because only external noise goes through the template. The LAM and PTM offer similar interpretations of the shapes of the TvN curves measured in Experiment 1, Chapter 3. In the PTM, changes in the low external noise portion of the curve are the result of either an increase in template gain (termed signal enhancement) or a reduction in contrast-invariant internal noise (termed additive noise reduction). These processes are mathematically equivalent and hence cannot be differentiated. Changes in the high external noise portion of the curve result from external noise exclusion, which affects both template efficiency and template gain. Finally, for both the LAM and PTM, reduction of contrast-dependent (e.g., multiplicative) internal noise results in uniformly lowered thresholds at all external noise levels. Recall that the TvN curves in Experiment 1 (Chapter 3) showed an age-related increase in thresholds across all external noise levels, but that this was most pronounced at low external noise levels. In the early-noise LAM this is interpreted as an age-related increase in additive internal noise and in k. The results of Experiment 2 (Chapter 3) suggested that there was no age difference in I/E ratio in high external noise conditions, suggesting the age difference in k found in the first experiment was not influenced by multiplicative internal noise. That is, increased face discrimination thresholds were interpreted to be the result of an age-related increase in additive internal noise and an age-related decrease in calculation efficiency. The PTM would interpret these data as a combination of signal enhancement/additive noise reduction and external noise exclusion. That is, the PTM would account for the age difference as reflecting a combination of an age-related decrease in template efficiency, which increases threshold in high-noise conditions, and an increase in additive internal noise (or, equivalently, a reduction in signal gain), which increases threshold in low-noise conditions. To summarize, both an early- and late-noise model appear to fit the data presented in Chapter 3, and until we are able to locate where in the visual system the internal noise occurs, selecting one model over another is merely an issue of parsimony.

5.3 Future Directions

A commonly held view in the face perception literature is that our expertise with upright faces is due to holistic processing, which presumably contributes to faster and more accurate face identification (see Maurer et al., 2002 for a review; but see Sekuler et al., 2004; Gaspar et al., 2008b; Konar et al., 2010 for an alternative view). In this framework, a number of tasks are thought of as behavioural markers of holistic processing, such as the face inversion effect (FIE; Yin, 1969), the composite face effect (CFE; Young et al., 1987), the whole-part effect (WPE; Tanaka and Farah, 1993), Thatcher Illusion (Thompson, 1980), feature spacing discrimination (Diamond and Carey, 1986). Any of these effects could be examined with the psychophysical methods used in this thesis. For example, noise masking and response consistency methods have been used to show that, in younger observers, decrements in performance caused by face inversion (Albonico et al., 2018; Gaspar et al., 2008b) and contrast-reversal (Gaspar et al., 2008b) of faces are due to changes in efficiency, not additive or multiplicative internal noise (Gaspar et al., 2008b). Gold et al. (1999, 2004) showed that perceptual learning in face discrimination and identification tasks increases calculation efficiency, but has no significant effects on additive and multiplicative internal noise. Finally, Shafai and Oruc (2018) found that increased additive internal noise is responsible for the other-race effect, but that efficiency across same- and other-race faces did not differ.

Some evidence suggests older adults are impaired at holistic processing (Chaby et al., 2011; Murray et al., 2010; Schwarzer et al., 2010; Slessor et al., 2013) while other findings suggest older adults rely more heavily on holistic processing than younger adults (Adduri and Marotta, 2009; Daniel and Bentin, 2012; Konar et al., 2013; Meinhardt-Injac et al., 2014), even though it results in worse performance (Konar et al., 2013; Meinhardt-Injac et al., 2014). Thus, one reasonable extension of my work would be to use the Face Inversion Effect to examine how holistic processing is affected by aging. Younger observers rely on similar sources of information for both upright and inverted faces (Sekuler et al., 2004; Gaspar et al., 2008a; Willenbockel et al., 2010). As mentioned previously, in younger adults the deficit incurred by inversion is due to changes in calculation efficiency rather than internal noise (Gaspar et al., 2008b), but it is not known if similar effects occur in older adults. Such experiments could help explain existing age-related differences in holistic processing. Additionally, one could examine whether the FIE is correlated with face identification accuracy in older adults. Individual differences in the face inversion effect of younger adults is correlated with horizontal bias (Pachai et al., 2013b), and the same may be true in older observers (Goffaux et al., 2015, though see Obermeyer et al., 2012). One could measure TvN curves for upright and inverted orientation filtered faces in order to examine age differences in calculation efficiency and internal noise. These suggested studies only concern judgements of face identity, and could be easily extended to other categories of faces (e.g., emotion, age) and other tasks (e.g., CFE, WPE).

The current thesis only considers age-related changes for judgements of facial identity for photographs of younger adults of the same age and ethnicity. However, older adults exhibit deficits on a range of face perception tasks. For example, older observers identify emotional expressions of anger, fear, and sadness less accurately than younger adults, but happiness is often spared and sometimes also disgust (Hayes et al., 2020; Isaacowitz et al., 2007; Ruffman et al., 2008). Such age differences might be the result of age-related changes in how information is spatially sampled from these faces. Emotions for which older adults tend to have the most difficulty contain diagnostic information in the upper-half of the face (i.e., eye/brow region; Baron-Cohen et al., 2001; Smith et al., 2005), and several studies support the idea that, relative to younger observers, older observers have decreased gaze-times to the upper-halves of these emotional faces (Murphy and Isaacowitz, 2010; Wong et al., 2005). This age difference in gaze pattern is correlated with identification accuracy on some of these emotions (Murphy and Isaacowitz, 2010; Sullivan et al., 2007; Wong et al., 2005, though see Grainger and Henry, 2020), but even after controlling for eye-fixation and other covariates, gaze pattern cannot completely explain the deficits (Murphy and Isaacowitz, 2010). This result suggests that – as was found in studies of face recognition memory – eye-tracking studies fail to completely capture the spatial sampling strategies of older observers. Indeed, using the Bubbles technique (Gosselin and Schyns, 2001), which provides a more direct measure of the information upon which observers base their decisions, Smith et al. (2018) found that younger and older adults relied on similar regions of all emotional faces, suggesting age-related differences in how information is spatially sampled is likely not responsible for age deficits in emotion identification. Replication of Smith et al. (2018) using classification images would further strengthen this claim. Horizontal structure also is important for emotion identification (Balas et al., 2015; Duncan et al., 2017; Huynh and Balas, 2014; Yu et al., 2018), and age-related changes in how horizontal information is used in different emotions might help explain why age-differences are larger for some emotions more than others.

5.4 Conclusion

Visual performance can be characterized as being constrained by two factors intrinsic to the observer: calculation efficiency and internal noise. My thesis demonstrates that both factors contribute to age-related decreases in face perception: In a series of experiments, I found that calculation efficiency was consistently lower, and equivalent input noise was consistently higher, in older observers compared to younger observers. The work in this thesis also demonstrates that the response classification, equivalent input noise, and response consistency paradigms are able to characterize age-related changes in face discrimination, and highlights the importance of considering the relative contribution of both calculation efficiency and internal noise to older adults' ability to perceive faces. More generally, my research contributes to our understanding of face perception and the factors constraining complex pattern vision in aging.

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