

**Age-related changes in multisensory integration mechanisms: A behavioral  
and event-related potential study.**

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von Frau Julia Diana Nannt, geb. Döhler

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Gutachter: Herr Prof. Dr. Hans Colonius  
Weitere Gutachter: Frau Prof. Dr. Adele Diederich

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Julia Diana Nannt, geb. Döhler

## Summary

The present study addressed the issue of audiovisual integration with special attention to differences between young and elderly adults. To investigate the age-related changes in integration performance, a number of experiments were conducted, in which participants were presented with a stream of unimodal auditory, unimodal visual, and bimodal audiovisual stimuli. The additional impact of stimulus intensity and stimulus onset asynchrony on the reaction time and the event-related potentials (ERPs), which are related to audiovisual integration, were assessed with adults aged 18-32 and 65-72 years.

In a reaction time experiment, subjects were instructed to respond as fast as possible to a visual stimulus while ignoring the additionally presented auditory stimulus. For both age groups, shorter reaction times were observed the higher the stimulus intensity was and the more the auditory stimulus preceded the visual stimulus. Elderly adults exhibited slower reaction times to unimodal stimuli when compared to young adults, but showed similar reaction times to bimodal stimuli. Moreover, both age groups had a similar amount of multisensory enhancement, that is, elderly adults did not benefit more from a bimodal stimulus than young adults.

In an electroencephalography experiment, subjects were instructed to perform a perceptual task with no demand for a manual response. To determine the proportion of multisensory interaction in the early (40-90 ms) and the later (100-200 ms) latency range, the ERP to the bimodal stimulus was compared to the sum of the two unimodal ERPs. Both age groups did not differ in the early latency range, but, for the later positive interaction component at around 150 ms (P150), elderly adults exhibited longer latencies than young adults. Furthermore, the latency of the P150 was shorter for stimuli of high as compared to stimuli of low intensity, and the amplitude of the P150, and thus the proportion of multisensory interaction, was highest when the auditory stimulus preceded the visual stimulus.

## Zusammenfassung

Die vorliegende Studie beschäftigte sich mit dem Thema der audiovisuellen Integration, wobei die Aufmerksamkeit besonders auf den Unterschieden zwischen jungen und älteren Erwachsenen lag. Um die altersbedingten Veränderungen in der Integrationsleistung untersuchen zu können, wurden verschiedene Experimente durchgeführt, in denen die Probanden eine Reihenfolge von unimodal auditiven, unimodal visuellen und bimodal audiovisuellen Stimuli präsentiert bekamen. Die zusätzlichen Auswirkungen der Stimulusintensität und der Stimulus Onset Asynchronität auf die Reaktionszeit und die ereigniskorrelierten Potentiale (EKPs), die beide im Zusammenhang mit der audiovisuellen Integrationsleistung stehen, wurden in erwachsenen Probanden im Alter von 18-32 und 65-72 Jahren untersucht.

In einem Reaktionszeitexperiment wurden die Versuchspersonen aufgefordert schnellstmöglich auf visuelle Stimuli zu reagieren, zusätzlich präsentierte auditive Stimuli jedoch zu ignorieren. Für beide Altersgruppen zeigten sich kürzere Reaktionszeiten je höher die Intensität des Stimulus war und je weiter der auditive Stimulus vor dem visuellen Stimulus präsentiert wurde. Ältere Probanden reagierten im Vergleich zu den jungen Probanden langsamer auf unimodale Stimuli, jedoch ähnlich schnell auf bimodale Stimuli. Des Weiteren, zeigten beide Altersgruppen einen ähnlichen Anteil an multisensorischer Verbesserung (*multisensory response enhancement*), sprich ältere Probanden profitierten im Vergleich zu jungen Probanden nicht mehr von bimodalen Stimuli.

In einem Elektroenzephalographie-Experiment wurden die Probanden gebeten eine perzeptuelle Aufgabe ohne Abgabe einer manuellen Antwort durchzuführen. Um den Anteil der multisensorischen Interaktion im frühen (40-90 ms) und späteren (100-200 ms) Latenzbereich zu ermitteln, wurde das EKP auf den bimodalen Stimulus mit der Summe der EKPs auf die beiden unimodale Stimuli verglichen. Die beiden Altersgruppen unterschieden sich nicht im frühen Latenzbereich, jedoch zeigte sich, dass die älteren Probanden längere Latenzen für die spätere, positive Interaktionskomponente bei ca. 150 ms (P150) aufwiesen als junge Probanden. Ferner war die Latenz der P150 kürzer für Stimuli mit hoher als für Stimuli mit niedriger Intensität. Die Amplitude, und somit auch der Anteil der multisensorischen Interaktion, war am höchsten wenn der auditive Stimulus vor dem visuellen Stimulus präsentiert wurde.

## Contents

Acknowledgements .....	1
1. Introduction .....	2
1.1. Age-related changes .....	2
1.1.1. Age-related changes in the visual system .....	3
1.1.2. Age-related changes in the auditory system .....	4
1.2. Multisensory integration .....	5
1.2.1. Multisensory integration in young and elderly adults .....	7
1.3. Fundamentals of the electroencephalography .....	8
1.3.1. Multisensory integration measured in EEG .....	10
1.4. Purpose of the present study .....	13
2. Experiment 1: Reaction time experiment .....	14
2.1. Materials and methods .....	15
2.1.1. Participants .....	15
2.1.2. Procedure and stimulus conditions .....	15
2.1.3. Data analysis .....	18
2.2. Results .....	21
2.3. Discussion .....	30
3. Experiment 2: EEG experiment based on Senkowski et al. (2011) .....	38
3.1. Materials and methods .....	38
3.1.1. Participants .....	38
3.1.2. Procedure and stimulus conditions .....	39
3.1.3. EEG data acquisition and analysis of event-related potentials .....	41
3.2. Results .....	44
3.2.1. ERP waveforms .....	44
3.3. Discussion .....	49
4. Experiment 3: EEG experiment .....	51
4.1. Materials and methods .....	52
4.1.1. Participants .....	52

---

4.1.2. Procedure and stimulus conditions .....	52
4.1.3. EEG data acquisition and analysis of event-related potentials .....	56
4.2. Results .....	59
4.2.1. ERP waveforms.....	59
4.2.2. Audiovisual interactions.....	62
Audiovisual interactions from 100 to 200 ms .....	65
Early audiovisual interactions from 40 to 90 ms .....	72
Later audiovisual interactions at 215 and 255 ms .....	76
4.3. Discussion .....	81
Audiovisual interactions from 100 to 200 ms .....	81
Early audiovisual interactions from 40 to 90 ms .....	84
Later audiovisual interactions at 215 and 255 ms .....	86
Conclusion (EEG experiment).....	87
5. Summary and conclusion.....	88
6. References .....	90
7. Appendix.....	105

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## 1. Introduction

At all levels of psychological analysis, aging of sensory systems is of potentially great interest (Schieber, 2003). Age-related declines in sensory modalities can have a pervasive effect on health and welfare of elderly adults. For example, studies have shown that age-related changes in the visual or the auditory system are associated with increased risks of being involved in a traffic accident (Owsley et al., 1998), increased probability of falls occurring with age (Ivers et al., 1998) or even a deterioration in the quality of life (Appollonio et al., 1996). However, the orientation in the three-dimensional space is based on the processing of a variety of stimuli to which we are exposed in everyday life and which we perceive through our eyes, ears, taste or smell. Many previous studies have shown that a combination of information from distinct sensory modalities can influence our perception of the environment radically (Calvert et al., 2004; for a review). Thus, an important issue is, whether age-related changes exist in the processing of information from different sensory modalities.

### 1.1. Age-related changes

One central question in aging research is still whether elderly adults experience an impairment of specific processes (Falkenstein et al., 2006) or whether more general alterations are responsible for multiple distributed degradations (Li & Dinse, 2002; Reuter-Lorenz, 2002). It is well established that sensory acuity (Setti et al., 2011) in common with processes in cognition, premotion, and motion are affected by aging (Falkenstein et al., 2006; Li & Dinse, 2002). According to Li and Dinse (2002), neurobiological changes help to characterize the processes in the aging brain. These neurobiological changes can include alterations in anatomy, metabolism, and neurochemistry, as well as changes in functional circuitry (Arnsten, 1998; Cabeza, 2002; Raz, 2000). In terms of changes in the anatomy, in the last decades, it was suggested that the amount of cortical neurons is reduced with increasing age, which thus may lead to a decline in cognition (Brody, 1955). More recent studies by Morrison and Hof (1997) and Peters et al. (1998a) extenuated this view by reporting the number of cortical neurons to be stable during normal aging. However, Peters et al. (1998b) reported age-related differences in the structure of dendrites and synapses of neurons in the neocortex (layer 1) and a breakdown of myelin sheaths, which may contribute to general cognitive decline observed in elderly adults (Cerella, 1985). Furthermore, Park et al. (2001) described a number of age-related neurophysiological changes, such as an increased number of dendritic projections terminating on an indirect way in neuronal processing (Salthouse, 2000a), which thus may lead to a decrease in processing speed. This decrease in processing speed is a quantifiable indicator of cognitive reduction in age

(Fogerty et al., 2010). It starts around middle age (40-55 years; Grose et al., 2006; Grose & Mamo, 2010) and continues to deteriorate with age (Ross et al., 2007).

As part of the progressive degeneration during life, the loss of variability and the increase in vulnerability could be attributed to an ongoing deterioration of physical functions (Freiherr et al., 2013). Freiherr et al. (2013) assumed that especially interferences in the sensory system, which are closely related to intellect, influence our lives. Kaasinen et al. (2000) and Li (2003) reported that working memory, attention, and other cognitive control functions in the prefrontal cortex are affected by age-related neurochemical reductions. Working memory processes become less effective with aging (Craig, 2007; Fabiani, 2012), which could partly be due to a reduced effectiveness of inhibitory processes with increasing age (Hasher & Zacks, 1988). Even an impaired attention could be one reason for specific deficits in working memory (Gazzaley et al., 2005). For example, when attentional processes become less efficient (Craig, 2007; Fabiani, 2012), elderly adults have difficulties in selecting a certain modality channel and segregating specific signals from redundant signals or background noise (Kramer & Madden, 2007). Besides a decline in working memory and attentional control, motor speed and executive functions deteriorate with increasing age as well (Falkenstein et al., 2006).

The amount of an age-related decline in sensory and perceptual functions varies within and between different sensory modalities. Impairments in the visual and the auditory system play an important role in the poorer performance (e.g. in response times) observed in elderly adults (Corso, 1971). Schneck et al. (2012) reported that the probability for deteriorations in the visual and the auditory system increases with age, manipulating the quality of life (Brooks & Hallam, 1998).

### **1.1.1. Age-related changes in the visual system**

In respect of the visual system, about 4 % of the elderly adults with an age of 65 to 74 years experience difficulties in seeing, even with glasses (Muñoz et al., 2000). Changes in the aging visual system could be observed in the cornea, pupil, lens, photoreceptors or even retinal ganglion cells. Referred to the cornea, the retinal image could considerably be changed by alterations in the curvature of the cornea (Schieber, 2006). Studies reported that this increased curvature in elderly adults occurs above 50 years of age (Baldwin & Mills, 1981; Fledelius, 1988). With increasing age also the average diameter of the pupil seems to become smaller, as referred to Loewenfeld (1979), who mentioned that the diameter of the pupil decreases from 7-8 mm by an age of 20 years to 4 mm by 80 years of age. This decrease in the pupil size, a condition referred to as pupillary miosis (Schieber, 2006), leads

to a reduced amount of light reaching the retina (Birren et al., 1950). Regarding the lenses, an increase in thickness (Corso, 1971) and blurring (Weale, 1963) could be observed as well as a decrease in ability of accommodation (Schieber, 2006). Because of decreasing accommodative power, an adult in the midforties possibly has difficulties in focusing upon objects within arm length (presbyopia; Hofstetter, 1965). With respect to age-related differences in the photoreceptors, several studies reported a dramatic loss in the number of rods (Curcio et al., 1990; Gao & Hollyfield, 1992; Panda-Jonas et al., 1995). The density of rods in the central retina (3-10°) declines between an age of 34 and 90 years by 30 % (Curcio et al., 1993), but a reduction in the density of cones seems to occur in the aging visual system as well (Gartner & Henkind, 1981).

In addition, changes in the visual system, such as a reduced amount of retinal ganglion cells (Curcio & Drucker, 1993; Gao & Hollyfield, 1992), losses in the number of axons in the optic nerve (Repka & Quigley, 1989), and thinning of the neural layer of the retina (Lovasik et al., 2003) were reported. Going further along the ascending visual pathway, Devaney and Johnson (1980) reported on a 25 % decline in the number of cells in the primary visual (striate) cortex in a 60 year old adult. Nusbaum (1999) suggested that a decline in the aging visual system could arise in all stages reaching from perception of the stimulus to the processing. Ocular diseases such as cataracts, glaucoma, and the loss of the visual field (Nusbaum, 1999) could be possible reasons for a deterioration in the visual system with age. With normal aging the ability to detect motion in the visual field declines (Wojciechowski et al., 1995) as well as the visual acuity (Corso, 1971; Hirsch & Wick, 1960; Weale, 1975), the detection and discrimination of motion (Andersen & Atchley, 1995; Bennett et al., 2007), the discrimination of texture (Andersen et al., 2010), and the discrimination of the orientation of stimuli (Betts et al., 2007). Moreover, elderly adults have problems in focusing on objects with different distances and distinguishing between colours (Bozian & Clark, 1980).

### **1.1.2. Age-related changes in the auditory system**

Regarding the auditory system, over 30-35 % of adults with an age of 65-75 years and 40-50 % of adults with an age over 75 years experience a hearing loss (Davis, 1990; Gates & Cooper, 1991; Helzner et al., 2005; Nash et al., 2011). Elderly adults suffer not only from a deterioration of high-frequency hearing, but also from a decline in the perception of speech, especially in situations with noisy backgrounds (Divenyi et al., 2005; Dubno et al., 1997; Humes, 1996). The Committee on Hearing and Bioacoustics and Biomechanics (CHABA, 1988) described three main factors contributing to the decline in hearing abilities in elderly adults, including dysfunctions of the peripheral auditory system (Humes, 1996; Mazelová et al., 2003), deficits in the central auditory processing (Cruickshanks et al., 1998; Divenyi et al.,

2005; Jerger, 1992; Pichora-Fuller & Souza, 2003; Tremblay & Ross, 2007; Tremblay et al., 2003), and cognitive deficits (Craik, 2007; Salthouse, 2000b). One of the best known age-related changes in the auditory system is the loss of auditory acuity, a condition referred to as presbycusis (Schuknecht, 1955). The gradual presbycusis loss of hearing sensitivity observed in elderly adults has been studied extensively over the last decades and has been shown to be a common disorder in elderly adults with an age over 60 years (Brant & Fozard, 1990; Gates et al., 1990). Schuknecht (1964) attributed presbycusis to four distinct pathologies: (1) Sensory presbycusis, which describes an atrophy (loss of hair cells) in the basal end of the organ of Corti leading to a sudden high-frequency hearing loss; (2) Neural presbycusis, which involves a loss in the ability to discriminate speech caused by a loss in the neuron population in the auditory pathway; (3) Metabolic presbycusis, which describes a hearing loss of pure tones elicited by an atrophy of the stria vascularis; and (4) Mechanical presbycusis, in which the basilar membrane stiffens resulting in an increased amount of hearing loss in case of high frequency tones. Moreover, Sataloff (1965) reported that the population of afferent neurons in the cerebral cortex declines, which thus leads to hearing impairments and ineffective communications in adults with an age over 75 years.

Thresholds for the identification of words, consonants, and vowels increase with age (van Rooij & Plomp, 1990) as well as pure-tone thresholds. Depending on the frequency, longitudinal and cohort studies reported pure-tone thresholds to decline by about 5.5 to 9 dB per decade for the better ear (Davis et al., 1990; Gates et al., 1990; Ostri & Parving, 1991), while thresholds for the worse ear often decline nearly 50 % faster (Divenyi et al., 2005). In addition to age-related threshold differences, auditory working memory has also been mentioned to change with age (Golob & Starr, 2000).

However, one opportunity to diminish negative effects of the aforementioned deteriorations in the visual and the auditory system is to use information from both sensory modalities (DeLoss et al., 2013).

## 1.2. Multisensory integration

A challenging task for the brain is to process information across different sensory modalities as transmission velocity and neural transduction vary among the different senses (Setti et al., 2014). For example, light travels through the air much faster than sound (300,000,000 m/s vs. 330 m/s) and thus reaches the sensory receptors faster (Vroomen & Keetels, 2010). As opposed to this, from the sensory receptors, the neural processing time for an auditory stimulus is faster than those for a visual stimulus (Vroomen & Keetels, 2010). In case of comparing reaction times (RTs) to unimodal auditory and unimodal visual stimuli, RTs were found to be shorter for the auditory modality (Diederich & Colonius, 2004a).

Additionally, it is well known that the RT to a unimodal stimulus is influenced by stimulus intensity as well. With increasing stimulus intensity a speed-up in RT could usually be observed (Kohfeld, 1971).

The process by which information from different sensory modalities, such as vision, audition, taste, and smell, are combined is defined as *multisensory integration* (physiological), or crossmodal interaction (behavioral; Stein et al., 2009). This combined information is able to influence sensation, perception, decision, and behavior. Numerous studies, both behavioral and neurophysiological, investigated the issue of multisensory integration and reported that combined information can often lead to better or more robust perceptual performance (Ernst & Bühlhoff, 2004; for a review, see Calvert et al., 2004). Two prominent effects show how information of the visual and the auditory modality interact. The ventriloquist effect describes the perception of speech coming from another spatial point than expected, affected by the visual influence of the obvious speaker (Howard & Templeton, 1966; Woods & Recanzone, 2004). A second effect, the McGurk effect, demonstrates that the content of information could also be changed by multisensory stimuli. Participants, who see a person vocalizing the syllable /ga-ga/ whereas they hear /ba-ba/, typically perceive a /da-da/ (McGurk & MacDonald, 1976).

Even in plain detection or discrimination tasks with simple auditory and visual stimuli, multisensory interactions could be observed. Todd (1912) was the first, who used a task with a focused attention paradigm (FAP) to examine multisensory interaction. During a FAP task participants have to respond to a predefined target modality while ignoring stimuli of any other modality. In contrast to a FAP task, in a task using a redundant target paradigm (RTP) participants have to respond to a set of stimuli from different sensory modalities as soon as a stimulus of any modality has been perceived. During Todd's (1912) FAP task, subjects had to respond only to a visual target stimulus while ignoring all other stimuli of non-target modalities. Todd obtained shorter RTs to bimodal audiovisual stimuli compared to unimodal visual stimuli. His results have often been replicated. The speed-up in RT, when stimuli of two different modalities were combined (e.g. visual and auditory) as compared to stimuli of one of the modalities (visual only or auditory only), was found in many studies, in which participants had to respond to any received stimulus (RTP; e.g. Diederich & Colonius, 1987; Hershenson, 1962) as well as in studies, in which participants had to perform a FAP task (e.g. Morrell, 1968; Rach & Diederich, 2006; see, for a review, Calvert et al., 2004). This observable facilitation in RT has also been termed *intersensory facilitation* (Welch & Warren, 1986).

In more detail, multisensory integration is influenced by the alignment of the stimuli. Unimodal stimuli have to occur in close temporal and spatial alignment in order to achieve

optimal integration results (Meredith & Stein, 1986a). For the contrary case, the amount of intersensory facilitation is decreased with increasing temporal separation (“temporal rule”, Diederich & Colonius, 2004a, 1987; Hershenson, 1962; Miller, 1986; Morrell, 1968) as well as with increasing spatial separation (“spatial rule”, Amlôt et al., 2003; Arndt & Colonius, 2003; Frens et al., 1995; Harrington & Peck, 1998). Thus, the intersensory effect could be observed as a speed-up (facilitation) or a slowdown (inhibition) of the response, based on the spatiotemporal alignment of the target and non-target stimuli (Amlôt et al., 2003; Diederich & Colonius, 2007). In addition to this, behavioral facilitation would be more robust when bimodal stimuli are presented at low intensity as compared to high intensity. This condition, also referred to as “the principle of inverse effectiveness” (Corneil et al., 2002; Diederich & Colonius, 2004a; Rach & Diederich, 2006), was first described in a study by Stein and Meredith (1993), where minimally effective constituent unisensory stimuli elicit maximal multisensory response enhancements.

### **1.2.1. Multisensory integration in young and elderly adults**

In the past, behavioral research on age-related differences in multisensory integration mainly focused on interaction between the visual and the auditory system. Some studies suggested that congruent information from different sensory modalities is combined more in elderly adults than in their young counterparts. For example, Laurienti et al. (2006) conducted a RTP task with unimodal visual (red and blue coloured discs), unimodal auditory (verbalization of the word for the colour), and bimodal audiovisual stimuli (simultaneously presented auditory and visual stimuli) and compared RTs between two age groups. Laurienti et al. (2006) reported shorter RTs to bimodal stimuli compared to unimodal stimuli in both age-groups, but RTs to both unimodal and bimodal stimulus types were significantly slower for elderly adults compared to young adults. In contrast to this, they observed a greater intersensory facilitation for elderly adults, indicating that the elderly adults benefit more from bimodal information. According to Diederich et al. (2008), the underlying explanations for this effect remain contentious. Either age-related differences in the processing of multisensory information or a general slowing in elderly adults (Cerella, 1985) could be responsible for this observation. In accordance with Laurienti et al. (2006), Peiffer et al. (2007) and Diederich et al. (2008) obtained similar results, showing enhanced multisensory integration effects in the elderly age group. Peiffer et al. (2007) utilized a RTP task with unimodal visual (two green light-emitting diodes), unimodal auditory (broadband white noise), and corresponding combined bimodal audiovisual stimuli that eliminated most high-order cognitive processes. Despite the fact that there was no significant difference in RTs to unimodal stimuli between the age groups, elderly adults showed significant higher multisensory enhancement than

young adults. Thus, the higher amount of multisensory enhancement cannot be solely ascribed to a general cognitive slowing (Diederich et al., 2008). In 2008, Diederich, Colonius, and Schomburg investigated at which stage multisensory processing differs between young and elderly adults. They conducted a FAP task with visual target (red light-emitting diode), auditory non-target (noise burst), and bimodal audiovisual stimuli where the onset of the auditory stimulus was shifted by a stimulus onset-asynchrony (SOA). Diederich et al. (2008) obtained shorter mean saccadic reaction times (SRTs) to bimodal stimuli as compared to unimodal stimuli for both age groups. SRTs were shorter for bimodal stimuli with large SOA than for bimodal stimuli with small SOA. Furthermore, elderly adults showed slower SRTs in all stimulus types, but exhibited larger multisensory integration effects compared to the young adults. Regarding the multisensory enhancement in elderly adults, the study by Stephen et al. (2010) reported conflicting results. Stephen et al. (2010) examined age-related multisensory integration with a perspective drawing of a soccer field with visual (near/far presentation of a soccer ball), auditory (quiet/loud tone corresponding to the proximity), and bimodal stimuli. They instructed their participants to respond as fast as possible with a button press when stimuli were near or far, relative to themselves. Similar to all aforementioned studies, Stephen et al. (2010) obtained longer RTs for the elderly age group, but, in contrast to other studies, did not find that elderly adults benefit more from the presentation of bimodal stimuli.

*Multisensory response enhancement* (MRE), also referred to as *crossmodal response enhancement*, is commonly measured by relating mean RTs in the bimodal stimulus type to that in the unimodal stimulus types (Colonius & Diederich, 2004). Conflicting results of previous studies reporting on a higher or a lower amount of MRE may be attributable to different task paradigms or different data analysis techniques.

In addition to behavioral RT experiments, electrophysiological experiments, such as electroencephalography, could also be used to assess multisensory integration.

### **1.3. Fundamentals of the electroencephalography**

By means of electroencephalography (EEG), the activity of the human brain can be monitored non-invasively and above scalp (extra-cortical) based on the production of electric fields by intracranial neurons (Freeman et al., 2009). Because of its high temporal resolution (Sharon et al., 2007), EEG can be used to examine the dynamic of coping processes in the brain during the recording of event-related potentials (ERPs).

Two main types of electrical activity are produced by neurons, action potentials and postsynaptic potentials, whereby ERPs almost always reflect rather postsynaptic potentials than action potentials (Luck, 2014). Postsynaptic potentials are voltages, which arise through

binding of the neurotransmitters to receptors on the membrane of the postsynaptic cell and lead to a graduated change in the voltage across the cell membrane by opening and closing ion channels (Luck, 2014). The outward of the postsynaptic membrane of a neuron can be more positive or more negative electrically charged than the rest of the postsynaptic membrane, depending on the excitatory or inhibitory impact of the synapse (Zschocke & Hansen, 2012). In case of an excitatory synapse, the positive charge of the outside of the cell is reduced in the area of the subsynaptic membrane. This leads to a relatively negative appearance of this area in comparison to remaining postsynaptic membrane areas (Zschocke & Hansen, 2012). From a physically point of view, the outside of the neuron in the area beneath the excitatory synapse becomes a negative pole, whereas the postsynaptic area becomes a positive pole (Zschocke & Hansen, 2012). This emerging polar structure of an electric field is called electric dipole (Zschocke & Hansen, 2012). Against the classical definition of a dipole in physics, dipoles here point towards the negative charge (Zschocke & Hansen, 2012). Postsynaptic potentials can thus be treated as field potentials of electric dipoles, whereby their field structure is affected by the tissue that encompasses the neuron (Zschocke & Hansen, 2012). The direction of dipoles, which is defined by the spatial structure and geometry of neurons, is crucial for the EEG (Zschocke & Hansen, 2012). Two essential types of neurons occurring in the cerebral cortex are pyramidal and stellate cells. Apical dendrites of the perpendicular oriented pyramidal cells head in the direction of the cortical surface (Luck, 2014) and branch out in the upper layers of the cortex. In consequence of this structure, vertical proceeding dipoles arise in the cortex (Zschocke & Hansen, 2012). A considerably larger amount of cortex neurons belongs to the type of stellate (or granular) cells, which are the principal interneurons of the cortex. Their numerous dendrites run in different directions in the cortex with the result that the different synaptic inflows to the electrical dipoles confront alternately.

Because dipoles from single neurons are very small, only summation of dipoles from many synchronously activated neurons can be recorded from a scalp electrode. Therefore, voltages of thousands or millions of neurons must occur at the same time and dipoles from individual neurons must be spatially aligned (Ebner & Deuschl, 2011). Due to the spatial structure and geometry, this summation is much more likely to appear in pyramidal cells than in stellate cells (Zschocke & Hansen, 2012). Therefore, ERPs mainly emerge from the cortical pyramidal cells. Moreover, the depictive representation of dipole fields in pyramidal cells is determined by brain convolutions (Zschocke & Hansen, 2012). Only dipoles in the vertex of a convolution, which lay radial to the cortical surface, can be fully recorded from a scalp electrode, whereas dipoles in the area of windings cannot be fully displayed due to their tangential alignment to the cortical surface (Cheyne & Weinberg, 1989; Zschocke & Hansen, 2012). If individual dipoles have an orientation of more than 90° to each other, a



partly cancellation will take place, with complete cancellation at 180° (Luck, 2014). Based on these facts about the generation of ERPs, it is important to note that only a fractional amount of the brain processes produces a scalp ERP “signature” (Luck, 2014).

Within a dipole field, potential differences arise through charge shifts at various tissue resistances (Zschocke & Hansen, 2012) and are inducible as cortical field potentials in EEG. From the positive to the negative pole, complete values are measurable along the field lines (Zschocke & Hansen, 2012). By linking the values of identical field potentials in the whole field, one will obtain equipotential lines (Zschocke & Hansen, 2012). But only when the lead electrodes refer to different equipotential lines, a quantifiable potential difference could be measured (Zschocke & Hansen, 2012). In case of a difference lead referring to equipotential lines with identical field potentials in both polarity and height, no potential differences will be registerable, not even when the neural activity is very high (Zschocke & Hansen, 2012). Hence, potential differences are only detectable if the lead electrodes come upon distinct equipotential lines.

Turning to the spatial and temporal resolution, ERPs provide an immediate and instantaneous measure of neural activity, which is mediated by neurotransmitters (Luck, 2014). EEG reveals, as well as magnetoencephalography (MEG), the highest temporal resolution available in non-invasive brain imaging (Hämäläinen et al., 1993). According to Luck (2014), under optimal conditions ERPs can have a temporal resolution of 1 ms or better, while in hemodynamic measures, such as positron emission tomography (PET) and functional magnetic resonance imaging (fMRI), the temporal resolution is limited to several hundred milliseconds due to the sluggish hemodynamic response. In contrast to the excellent temporal resolution in EEG, spatial resolution in this technique is relatively undefined (Steinmetz et al., 1989), because a pattern of ERP data can be explained by many configurations of internal ERP generators (Luck, 2014). Compared against EEG, the spatial resolution of fMRI reaches the millimeter range (Freeman et al., 2009). With fMRI, neural activities in all cortical, nuclear, and reticular structures can be imaged, whereas with EEG and MEG mainly activities of the cerebral cortex can be imaged (Freeman et al., 2009). Because of the fact that we are primarily interested in processing times and potential changes, EEG is the optimal technique to investigate multisensory integration in this study.

### **1.3.1. Multisensory integration measured in EEG**

In the last two decades, mechanisms of multisensory integration have been studied using ERPs. In most of these studies, interaction between two different senses was assessed by relating the ERP to the bimodal stimulus to the sum of the ERPs to the two unimodal stimuli.

For example, when investigating audiovisual integration, evidence for interaction between the visual and the auditory modality would be obtained when the amplitude of the bimodal audiovisual (AV) ERP differs from the sum of the unimodal auditory (A) and the unimodal visual (V) ERPs ( $A+V$ ). According to Barth et al. (1995), the ERP to the bimodal stimulus should be equal to the sum of the ERPs to the two unimodal stimuli, resulting in  $AV = A+V$ , if the senses operate independently. As opposed to this, one can deduce that the senses interact, if the sum of the ERPs to the two unimodal stimuli differs from the ERP to the bimodal stimulus ( $AV \neq A+V$ ; Barth et al., 1995). Hence, a deviation of the difference wave  $AV-(A+V)$  from zero could indicate a possible processing stage where integration of different sensory inputs may take place (Gondan & Röder, 2006). Several previous studies used this strategy and obtained interactions of the visual and the somatosensory system (e.g. Schürmann et al., 2002) as well as the auditory and the somatosensory system (e.g. Foxe et al., 2000; Gobbelé et al., 2003) and the visual and the auditory system (e.g. Fort et al., 2002b; Giard & Peronnet, 1999; Molholm et al., 2002; Vidal et al., 2008).

Teder-Sälejärvi et al. (2002) aroused criticism on this strategy. They argued that each type of unimodal and bimodal stimulus (A, V, and AV) is accompanied by a “common activity” (Gondan & Röder, 2006) including anticipatory potentials and motor responses. Considering the difference wave  $AV-(A+V)$ , this common activity is subtracted twice from the bimodal ERP (AV). One opportunity to delete this common activity in the difference wave  $AV-(A+V)$ , is to add the ERP to a “no-stimulus event” (blank, X). With this approach, the common activity would be eliminated (Gondan & Röder, 2006):  $AV-(A+V)+X$ . Another opportunity exists to avoid non-specific activities, such as late activities related to target processing (e.g., P300), motor processing or selection of a response, that would be common to all involved stimuli (A, V, and AV) (Fort et al., 2002b). Due of the fact that these activities usually occur after 200 ms poststimulus, the analysis could be restricted to the period of 0 to 200 ms (Fort et al., 2002b).

With use of the basic difference wave  $AV-(A+V)$ , previous studies suggested several different latency ranges and brain areas for multisensory integration. Most of these studies restricted the analysis period to 0-200 ms poststimulus, but used different task paradigms and stimuli to assess audiovisual integration. For example, Giard and Peronnet (1999) used a two-alternative forced-choice classification of unimodal auditory (540 vs. 560 Hz tone bursts), unimodal visual (horizontal vs. vertical ellipse), and bimodal audiovisual stimuli (combination of A and V, respectively). As compared to this, Molholm et al. (2002) utilized a RTP task with 1000 Hz tones as unimodal auditory stimuli, red disks on a black background as unimodal visual stimuli, and a combination of both as bimodal audiovisual stimuli. More recently, Senkowski et al. (2011) extended the investigation of audiovisual integration with RTP task by adding different stimulus intensities. As a consequence, auditory (1000 Hz pure

tones), visual (Gabor patches), and audiovisual stimuli (combination of both) were presented at low, middle, and high intensities.

In the period from 0 to 200 ms poststimulus, two latency ranges containing audiovisual interaction have consistently been mentioned: (1) the latency range from 100 to 200 ms; and (2) the latency range from 40 to 95 ms. The majority of previous studies reporting on audiovisual interaction in the latency range of 100 to 200 ms obtained effects in the range from 110 to 200 ms at occipital sites (Fort et al., 2002b; Gao et al., 2014; Giard & Peronnet, 1999; Molholm et al., 2002; Senkowski et al., 2007a; Teder-Sälejärvi et al., 2002). Further, some other studies found audiovisual interaction to occur in the latency ranges from 100 to 128 ms at centro-parietal sites (Molholm et al., 2002), from 105 to 140 ms at fronto-central sites (Fort et al., 2002b), from 120 to 180 ms at temporo-frontal sites (Fort et al., 2002b; Gondan & Röder, 2006), and from 150 to 185 ms at central sites (Giard & Peronnet, 1999; Vidal et al., 2008).

In terms of early audiovisual interaction in the latency range from 40 to 95 ms, most studies obtained effects at parieto-occipital (Cappe et al., 2010; Giard & Peronnet, 1999; Molholm et al., 2002) or occipital sites (Fort et al., 2002b; Van der Burg et al., 2011), whereas Vidal and colleagues (2008) reported on audiovisual interaction in the same latency range, but at fronto-central sites. Moreover, Senkowski et al. (2011) were not able to show a clear pattern of early audiovisual interaction at around 50 ms for stimuli of middle and high intensity, but revealed a clear pattern of effects for low intensity stimuli at around 50 ms at left posterior and right anterior sites.

All of the aforementioned studies on audiovisual integration with ERPs restricted their investigations to young participants with an age of 19 to 34 years only. In contrast, Yang et al. (2012) were the first, who designed a discrimination task with unimodal auditory (standard: 1000 Hz tone pip, target: white noise), unimodal visual (standard: black white block, target: red white block), and bimodal audiovisual stimuli (combination of both standards) to examine audiovisual integration in elderly adults with an age of 60 to 78 years. This study revealed two significant periods of audiovisual interaction. The first period ranged from 160 to 200 ms poststimulus at occipital sites, while the second period ranged from 300 to 600 ms at fronto-central sites. Although Yang et al. (2012) assessed audiovisual integration in elderly adults with ERPs, they did not link their results to a younger age group. Hence, to our knowledge, up to now, no study examined audiovisual integration in both young and elderly adults with EEG to make a point on possible age-related changes.

#### **1.4. Purpose of the present study**

To date, several behavioral studies were conducted reporting on differences in audiovisual integration mechanisms between young and elderly adults. However, electrophysiological studies dealing with this issue are lacking.

The purpose of the present study was to assess the performance of young and elderly adults in integrating visual and auditory information with both behavioral and electrophysiological experiments. Most of previous studies used unimodal auditory, unimodal visual, and bimodal audiovisual stimuli at merely one stimulus intensity or presented bimodal audiovisual stimuli with the same onset. In order to ascertain whether stimulus parameter such as stimulus intensity or SOA have an additional impact on audiovisual integration or whether these parameters affect the audiovisual integration performance in young and/or elderly adults, the aforementioned studies (see 1.2.1 and 1.3.1) were extended due to this aspect. A test of possible influences of age and varying stimulus parameters on the audiovisual integration mechanisms in young and elderly adults has been performed in one behavioral and two electrophysiological experiments, described hereafter.

## 2. Experiment 1: Reaction time experiment

The first experiment was designed to investigate audiovisual integration in young and elderly adults using a RT measurement in a FAP task. RTs were measured to a set of unimodal auditory, unimodal visual, and bimodal audiovisual stimuli. The main purpose of this behavioral experiment was to extend existing studies on audiovisual integration mechanisms by adding the stimulus parameters intensity and SOA. Diederich et al. (2008) compared the performance of young and elderly adults with a FAP task and utilized bimodal stimuli presented with varying SOAs. Based on this study, we decided to use bimodal stimuli with diverging SOAs for the present study as well; resulting in SOAs of -100, -50, and 0 ms (negative SOA indicate that auditory stimulus precedes the visual stimulus). In addition, we decided to present all unimodal and bimodal stimuli at both low and high stimulus intensities, to test whether the stimulus intensity has an additional influence on the audiovisual integration performance.

The labelling of the unimodal auditory and unimodal visual stimuli must be specified. During the experiment, one part of the unimodal visual stimuli was intermixed within the stream of bimodal audiovisual stimuli; the second part of the unimodal visual stimuli was presented separately of bimodal stimuli. Hereafter, intermixed unimodal visual stimuli are labelled as 'mixed unimodal visual stimuli' ( $V_m$ ), whereas separately presented unimodal visual stimuli are labelled as 'separated unimodal visual stimuli' ( $V_s$ ). Unimodal auditory stimuli were always presented separately from bimodal stimuli, whereby these were labelled as 'separated unimodal auditory stimuli' ( $A_s$ ).

Based on the theoretical background on multisensory integration measured by RT (see 1.2), two preconditions are made to the present data: (1) RTs to stimuli of high intensities are shorter than those to stimuli of low intensities (Kohfeld, 1971), and (2) RTs are, depending on the stimulus intensity, shorter to unimodal auditory stimuli than to unimodal visual stimuli (Diederich & Colonius, 2004a).

Given that both preconditions are successfully complied, three hypotheses could be generated.

**Hypothesis 1** is based on the results of a study by Diederich et al. (2008), where SRTs followed an ascending trend from bimodal stimuli with large SOA to bimodal stimuli with no SOA and, finally, largest SRTs for unimodal visual stimuli. The maximum facilitation is, according to Raab (1962), expected, when the SOA between the stimuli is equal to the time difference to the unimodal RTs. Hypothesis 1 claims that mean RTs to bimodal audiovisual stimuli increase with decreasing absolute SOA and is bounded by mean RT to unimodal visual stimuli in the mixed condition ( $V_m$ ). That is,

$$RT(AV_{-100}) < RT(AV_{-50}) < RT(AV_0) < RT(V_m).$$

**Hypothesis 2** is based on a study by Diederich et al. (2008), where elderly adults showed slower SRTs to bimodal audiovisual and unimodal visual stimuli. Hypothesis 2 states that elderly adults exhibit slower mean RTs as compared to mean RTs with young adults for unimodal auditory A, unimodal visual V, and bimodal audiovisual stimuli AV:

$$RT_{old}(AV,V,A) > RT_{young}(AV,V,A).$$

**Hypothesis 3** is based on studies by Diederich et al. (2008), Laurienti et al. (2006), and Peiffer et al. (2007). All of the aforementioned studies reported a higher multisensory response enhancement for elderly compared to young adults. Hypothesis 3 suggests that elderly adults show a higher amount of multisensory response enhancement (MRE) than young adults, indicating that elderly adults benefit more from a bimodal stimulus presentation, i.e.:

$$MRE_{old} > MRE_{young}.$$

## 2.1. Materials and methods

### 2.1.1. Participants

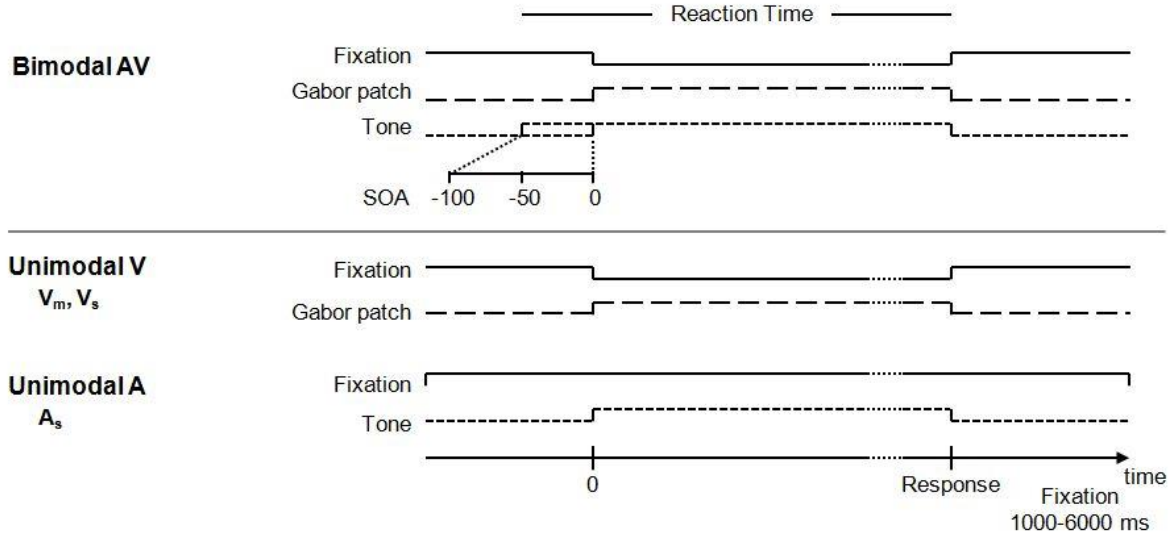
Twenty-five young and elderly paid adults participated in the present study. One young participant was excluded due to an excessive amount of missed trials. The remaining twelve young (aged 18-32 years,  $M = 23.5$ ,  $SD = 4.76$ , eight female) and twelve elderly adults (aged 65-72 years,  $M = 68.58$ ,  $SD = 1.83$ , twelve female) reported normal hearing and had normal or corrected-to-normal vision. Young adults were students at the University of Bremen, whereas the elderly adults were recruited from a pool of participants, who had registered for a former experiment at the Jacobs University Bremen. Participants provided a written informed consent and agreed with the anonymous storage, analysis, and publication of the data. For an expense allowance participants received 9 € per hour and a single flat rate for travel expense of 5 €. The experiment was conducted according to the principles expressed in the Declaration of Helsinki (1964).

### 2.1.2. Procedure and stimulus conditions

The experiment was conducted in a darkened room at the Jacobs University Bremen. Participants were seated 57 cm apart from a monitor and were required to fixate a fixation point (a white cross), which was visible at the center of the monitor during unimodal auditory stimuli and the inter-trial interval.

Participants received a randomized stream of unimodal auditory (A), unimodal visual (V), and bimodal audiovisual (AV) stimuli. All stimulus types were presented at low and high intensities. **Fig.1** illustrates the time course of the single unimodal and bimodal trials. Visual stimuli consisted of Gabor patches with vertical gratings (spatial frequency = 1 cycle/degree; Gaussian standard deviation = 1.5), which were presented at the center of the 19" computer monitor. Stimuli had a mean luminance constant at a level of 20 cd/m<sup>2</sup>. Michelson contrast  $((\text{maximal luminance} - \text{minimal luminance}) / (\text{maximal luminance} + \text{minimal luminance})) * 100 \%$  of low and high intensities was 10 % and 50 %, respectively. Auditory stimuli consisted of pure tones with a frequency of 1000 Hz, which were presented via two external stereo speakers placed to the left and to the right of the monitor. Auditory stimuli comprised of low and high intensities with sound-pressure levels of 40 and 65 dB, respectively. Bimodal audiovisual stimuli with low and high intensities consisted of corresponding combined unimodal stimuli (low A + low V = low AV and high A + high V = high AV). The auditory stimuli were shifted by an SOA of -100, -50 or 0 ms with negative values meaning that the non-target (A) was presented before the target (V). This experiment was designed without the bimodal stimulus presentation consisting of low/high and high/low combinations of the unimodal auditory and visual stimuli, due to the fact that the experiment would have been too demanding for the elderly age group, when this aspect had been included.

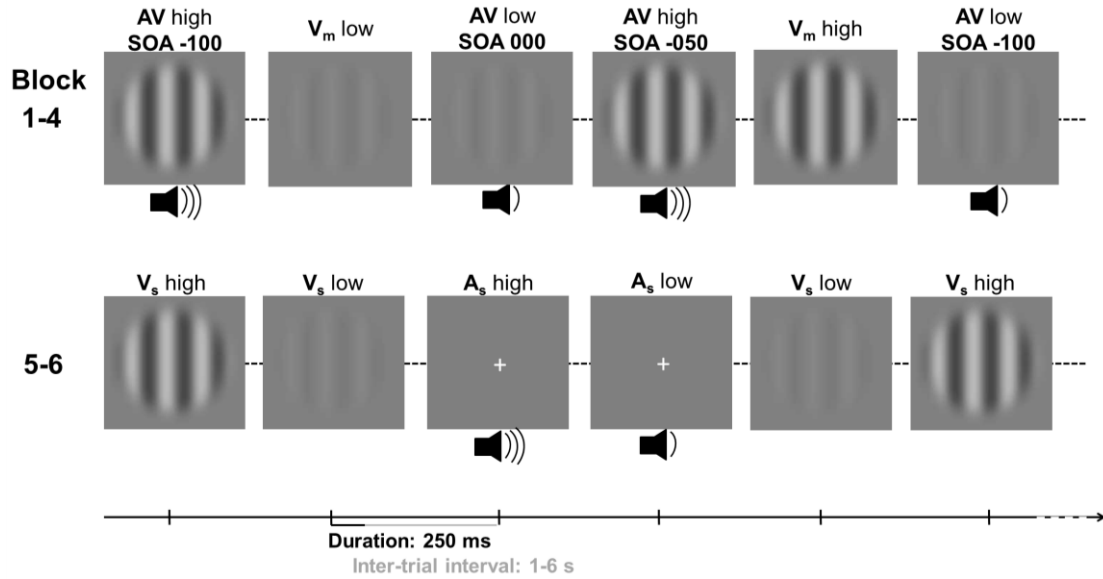
All unimodal ( $V_m$ ,  $V_s$ ,  $A_s$ ) and bimodal (AV) stimuli were presented for 250 ms (for auditory stimuli ( $A_s$ , AV): 10 ms rise and fall times). The entire session was divided into six blocks of about 5 minutes (160 trials in each block) of duration each. In blocks 1-4 only bimodal and mixed unimodal visual  $V_m$  stimuli were presented (condition 1), whereas in blocks 5-6 only separated unimodal auditory  $A_s$  and unimodal visual  $V_s$  stimuli were presented (condition 2). The twelve stimulus types ( $A_s$  low,  $A_s$  high,  $V_s$  low,  $V_s$  high,  $V_m$  low,  $V_m$  high, AV<sub>-100</sub> low, AV<sub>-50</sub> low, AV<sub>0</sub> low, AV<sub>-100</sub> high, AV<sub>-50</sub> high, AV<sub>0</sub> high) were offered in random order with equal frequencies over 80 trials. The inter-trial interval varied randomly (truncated exponential) between 1 and 6 s.



**Fig.1.** Time course of a single trial. The fixation was visible during the presentation of an auditory stimulus and the inter-trial interval, but not during the presentation of a visual stimulus. *Top:* Time course for a bimodal audiovisual stimulus (AV). The auditory stimulus (dotted) started 100 or 50 ms before or with the same onset of the visual stimulus (dashed). *Bottom:* Time course for unimodal visual ( $V_m$  and  $V_s$ ) and unimodal auditory ( $A_s$ ) stimuli.

**Fig.2** illustrates an exemplary experimental setup. During blocks 1-4, participants were instructed to perform a speeded button response with the dominant index finger to all visual stimuli ( $V_m$  and AV, FAP), whereas in blocks 5-6 they should respond to both separated unimodal visual  $V_s$  and unimodal auditory stimuli  $A_s$  (mixed unimodal target paradigm). Stimuli were presented through a standard PC with Linux operating system (Ubuntu 14.04 LTS). The monitor was driven through an AMD Radeon HD 7470 OEM video card. Custom-written C program (Dennis Ritchie & Bell Labs, Murray Hill, NJ, USA) using the OpenGL (Khronos Group Inc., Beaverton, OR, USA) and the OpenAL (Creative Technology Ltd., Singapore) libraries were used to control stimulus presentation and data acquisition. The exact timing between visual and auditory stimulation was adjusted to the millisecond level using an oscilloscope equipped with custom-built photo LEDs and a microphone, and the taking of the response time started only when the stimulus was visible on the screen. Latencies associated with the uptake of the response through the parallel port were below 2 ms.





**Fig.2.** Exemplary experimental setup. Participants were presented with a randomized stream of unimodal auditory (A), unimodal visual (V), and bimodal audiovisual (AV) stimuli of low and high intensity with varying stimulus onset asynchronies (SOAs) for the bimodal stimuli. During the blocks 1-4 bimodal audiovisual stimuli were intermixed with visual stimuli (V<sub>m</sub>), while participants were instructed to do a speeded button response to stimuli containing any visual amount (V<sub>m</sub> and AV). During the blocks 5-6 only separated unimodal visual (V<sub>s</sub>) and auditory stimuli (A<sub>s</sub>) were presented, while participants were instructed to respond to both stimulus modalities as fast as possible.

### 2.1.3. Data analysis

The analysis of the behavioral data of the RT experiment included the tests of two preconditions and three hypotheses (see page 14). If both preconditions stating that (1) RTs to stimuli of high intensity are shorter than those to stimuli of low intensity and (2) RTs to unimodal auditory stimuli are shorter than RTs to unimodal visual stimuli were satisfied, testing of the three central hypotheses would follow.

To investigate Precondition 1, saying that RT to stimuli of high intensities were faster than those to stimuli of low intensities, a Wilcoxon signed-rank test for two dependent samples was conducted using all stimulus modalities (A, V, AV). A second Wilcoxon signed-rank test was performed to examine whether RTs to unimodal auditory stimuli were faster than RTs to unimodal visual stimuli (Precondition 2).

In the next step of the analysis, Page's trend test (Bortz & Lienert, 2008) was computed, since the RTs were not normally distributed and an ascending trend hypothesis could be made. This test was calculated to examine if RTs increase in a predefined order, from bimodal stimuli with an SOA of -100 ms to bimodal stimuli with an SOA of 0 ms and, finally, to mixed unimodal visual stimuli V<sub>m</sub> (Hypothesis 1). The null hypothesis for Page's trend tests is that no difference could be observed between the four stimulus types. Accordingly, the following order was assumed as alternative hypothesis H<sub>A1</sub>:

$$RT(AV_{-100}) < RT(AV_{-50}) < RT(AV_0) < RT(V_m).$$

In order to clearly determine whether RTs follow the predefined order, with fastest RTs to bimodal and slowest RTs to mixed unimodal visual stimuli, the trend test was performed for each pairing of age group and stimulus intensity. Hence, four trend tests were conducted:

Test I. Age group 'young', Intensity 'low'

Test II. Age group 'young', Intensity 'high'

Test III. Age group 'old', Intensity 'low'

Test IV. Age group 'old', Intensity 'high'

In addition to that, a repeated-measures analysis of variance (ANOVA) was conducted to investigate whether SOA or stimulus intensity had a general influence on the RT between the two age groups. The within-subject factors 'SOA' (-100, -50, 0 ms) and 'Stimulus Intensity' (low, high), and the between-subject factor 'Age group' (young, old) were used. Geisser-Greenhouse corrections were used in reporting the  $p$  values when appropriate.

Following this, a rank test for repeated-measures designs with one between-subject and one within-subject factor, the so-called 'F1-LD-F1' design by Brunner et al. (2002), was performed to determine a possible RT difference between both age groups and both stimulus intensities (Hypothesis 2). This test is an equivalent to the two-factorial repeated-measures ANOVA with a two-stepped group factor 'Age' (young, old) and a two-stepped factor 'Stimulus Intensity' (low, high). It was used because of the violated normal distribution of the RTs. The rank test examines the two main factor hypotheses and also the interaction hypothesis of the two factors. For either the tests of the main factor hypotheses or the test of the interaction hypothesis, the null hypothesis is that no difference could be observed in the RTs. Thus, the following alternative hypotheses  $H_{A2.1}$ ,  $H_{A2.2}$ , and  $H_{A2.3}$  were stated. For the main factor 'Age', the alternative hypothesis  $H_{A2.1}$  stated a difference between the RTs for young and elderly adults. Second, alternative hypothesis  $H_{A2.2}$  for the main factor 'Stimulus Intensity' indicated a difference between RTs to low and high stimulus intensities. The third alternative hypothesis  $H_{A2.3}$  stated an interaction between the two main factors. For each stimulus type ( $A_s$ ,  $V_s$ ,  $V_m$ ,  $AV_{-100}$ ,  $AV_{-50}$ ,  $AV_0$ ) the rank-score test was conducted separately.

Next, the multisensory, or crossmodal, response enhancement (MRE) was computed to examine the proportion of intersensory facilitation or inhibition (Colonius & Diederich, 2004). With this measure mean RTs to bimodal stimuli are related to RTs to unimodal stimuli. In a FAP with a visual target modality, Colonius and Diederich (2012) defined MRE for visual and visual-auditory stimuli with expected reaction times  $E[RT_V]$  and  $E[RT_{AV}]$  as:

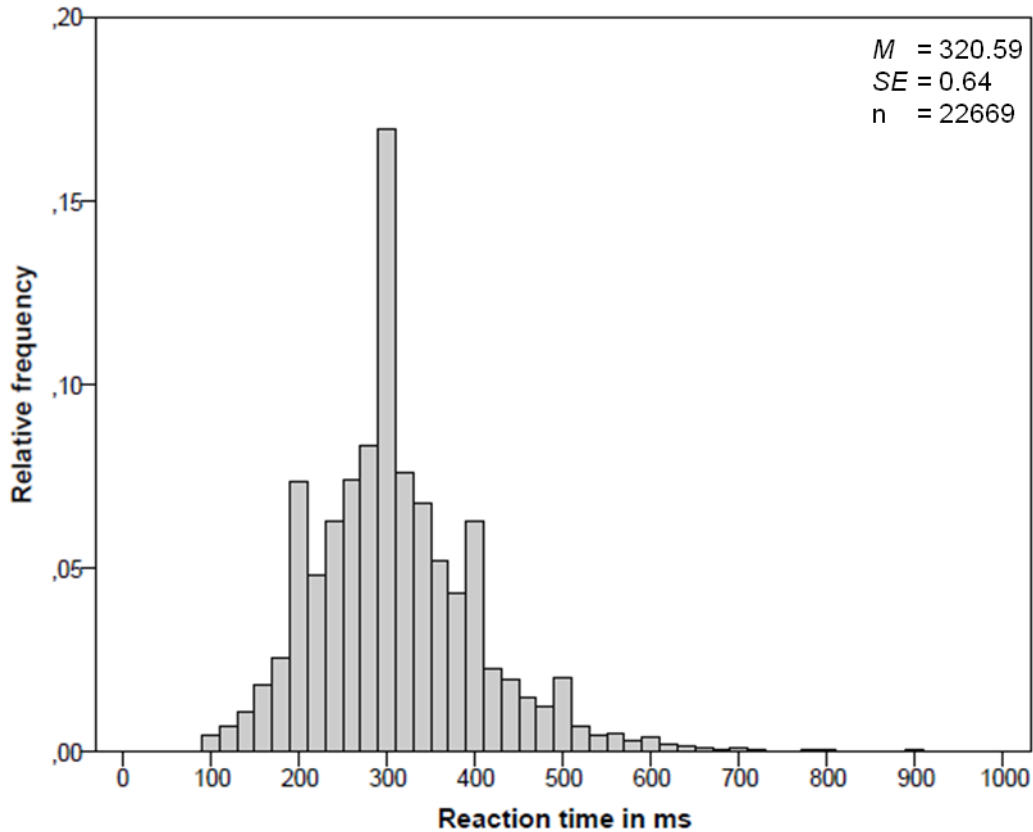
$$MRE = \frac{E[RT_V] - E[RT_{VA}]}{E[RT_V]} \cdot 100 \quad (1)$$

For each participant the MRE was calculated over the six bimodal stimulus types ( $AV_{-100}$  low,  $AV_{-50}$  low,  $AV_0$  low,  $AV_{-100}$  high,  $AV_{-50}$  high,  $AV_0$  high) relative to the expected RT to mixed unimodal visual stimuli  $V_m$ . Following this, the mean MREs for each age group were computed. To investigate if SOA or stimulus intensity had a general influence on the MRE between both age groups (Hypothesis 3), a rank test for repeated-measures designs with one between-subject and two within-subject factors, the so-called 'F1-LD-F2' design by Brunner et al. (2002), was performed. 'SOA' (-100, -50, 0 ms) and 'Stimulus Intensity' (low, high) served as within-subject factors, whereas 'Age' (young, old) served as between-subject factor.

This rank test examined the three main factor hypotheses, the three first-order interaction hypotheses ('Stimulus Intensity' \* 'SOA', 'Stimulus Intensity' \* 'Age', and 'SOA' \* 'Age'), and the second-order interaction of all three factors ('Stimulus Intensity' \* 'SOA' \* 'Age'). For either the tests of the main factor hypotheses or the tests of the interaction hypotheses, the null hypothesis is that no difference could be observed in the RTs. Accordingly, the following alternative hypotheses  $H_{A3.1}$  -  $H_{A3.7}$  were stated. For the main factor 'Age' the alternative hypothesis  $H_{A3.1}$  stated a difference between the RTs for young and elderly adults. Second, hypothesis  $H_{A3.2}$  for the main factor 'Stimulus Intensity' indicated a difference between RTs to low and high stimulus intensities. The third alternative hypothesis  $H_{A3.3}$  for the main factor 'SOA' stated a difference between RTs presented with varying SOAs. The three alternative hypotheses regarding the interactions between the main factors indicated a difference between the factors 'Stimulus Intensity' and 'SOA' ( $H_{A3.4}$ ), the factors 'Stimulus Intensity' and 'Age' ( $H_{A3.5}$ ), and the factors 'SOA' and 'Age' ( $H_{A3.6}$ ). A second-order interaction between all three factors is stated by  $H_{A3.7}$ .

## 2.2. Results

The Kolmogorov-Smirnov test for one sample was used to verify that the RTs are normally distributed. As to be expected for the sample size in the current RT experiment, the Kolmogorov-Smirnov test revealed violation of the normal distribution assumption ( $p < 0.001$ ; see **Fig.3**). Thus, all essential tests in the following analysis of the data were conducted as non-parametric tests. The only exception is the ANOVA, which could be seen as an extension and confirmation of Page's trend test.



**Fig.3.** Distribution of the RTs. RTs were not normally distributed.

RTs were first screened for anticipation errors ( $RT < 100$  ms) and misses ( $RT > 1000$  ms), resulting in the removal of 3.2 % of the total amount of trials. About 1.8 % of the trials were removed for the young and 1.4 % were removed for the elderly group, indicating that the young group did more mistakes during the entire experiment. Considering the bimodal audiovisual stimuli, most errors and misses were made during the presentation of bimodal stimuli with an SOA of -50 ms (0.52 %), while the presentation of bimodal stimuli with an SOA of -100 ms and 0 ms resulted in the removal of 0.44 % and 0.36 % of the trials, respectively. The presentation of mixed unimodal visual stimuli  $V_m$  and separated unimodal visual  $V_s$  and auditory stimuli  $A_s$  resulted in 0.56 % ( $V_m$ ), 0.74 % ( $V_s$ ), and 0.61 % ( $A_s$ ) errors and misses. Hence, most mistakes were made during the presentation of separated

unimodal visual stimuli  $V_m$ . **Tab.1** summarizes the different error types and corresponding percentages.

**Tab.1.** Percentages of trials with misses and errors. Misses and errors are shown as percentages (%) of the total amount of trials, sorted by stimulus type and age group.

Age		Stimulus type						Total
		$AV_{-100}$	$AV_{-50}$	$AV_0$	$V_m$	$V_s$	$A_s$	
<b>RT&lt;100</b>	<b>young</b>	0.026	0.052	0.009	0.026	0.017	0.017	<b>0.147</b>
	<b>old</b>	0.009	0.009	0.009	0.017	0.000	0.009	<b>0.053</b>
<b>RT&gt;1000</b>	<b>young</b>	0.208	0.269	0.191	0.278	0.408	0.304	<b>1.658</b>
	<b>old</b>	0.200	0.191	0.148	0.234	0.313	0.278	<b>1.364</b>

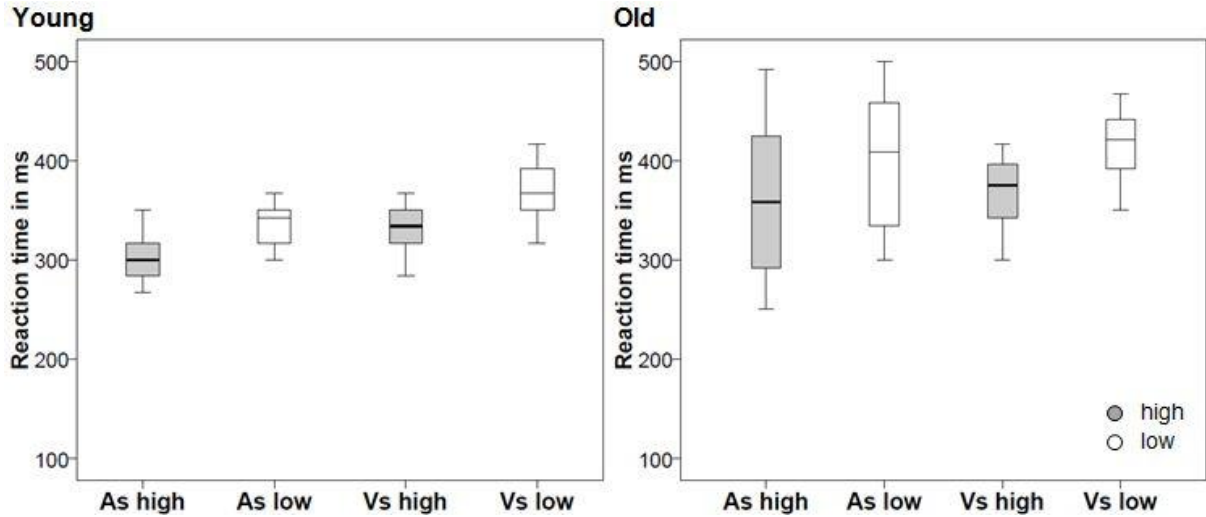
Consistent for both age groups, mean RTs to bimodal stimuli were generally shorter than to all types of unimodal stimuli ( $A_s$ ,  $V_s$ ,  $V_m$ ) and mean RTs to stimuli of high intensity were generally shorter compared to stimuli of low intensity. Furthermore, the young age group showed generally faster RT than the elderly age group. **Tab.2** contains the means, medians, standard deviations, and standard errors of both age groups for the different stimulus types presented at high and low stimulus intensity.

**Tab.2.** Mean RT, median, standard deviation (SD), and standard error (SE) for all bimodal (AV<sub>-100</sub>, AV<sub>-50</sub>, AV<sub>0</sub>) and unimodal (A<sub>s</sub>, V<sub>s</sub>, V<sub>m</sub>) stimuli (for young and old: n = 12).

Stimulus	Intensity	Age	RT	Median	SD	SE
AV <sub>-100</sub>	high	young	194.92	194.00	24.83	17.17
		old	217.50	202.00	53.65	15.49
	low	young	233.54	234.00	28.09	8.11
		old	276.33	275.50	62.89	18.15
AV <sub>-50</sub>	high	young	235.50	241.50	19.84	5.73
		old	256.17	250.00	39.21	11.31
	low	young	270.42	267.00	21.12	6.10
		old	303.46	300.00	41.48	11.97
AV <sub>0</sub>	high	young	267.58	267.00	23.18	6.69
		old	281.42	275.00	32.10	9.27
	low	young	303.75	312.50	21.17	6.11
		old	328.63	325.50	34.53	9.97
A <sub>s</sub>	high	young	298.79	300.00	23.89	6.90
		old	361.83	358.50	75.70	21.85
	low	young	335.58	342.00	23.10	6.67
		old	400.92	408.50	67.87	19.59
V <sub>s</sub>	high	young	330.83	334.00	24.34	7.03
		old	367.50	375.00	34.58	9.98
	low	young	369.63	367.00	27.39	7.91
		old	414.63	421.00	39.50	11.40
V <sub>m</sub>	high	young	322.58	333.50	22.73	6.56
		old	339.00	350.00	27.19	7.85
	low	young	357.83	350.00	31.43	9.07
		old	389.75	400.00	41.98	12.12

Precondition 1 claimed shorter mean RTs to stimuli of high intensity compared mean RTs to stimuli of low intensity. Wilcoxon signed-rank test showed a significant difference ( $T = -10.314$ ,  $p < 0.001$ ) between the RTs (**Fig.4**). Shorter mean RTs existed for stimuli of high intensity ( $M = 289.53$ ,  $SD = 65.05$ ) than for stimuli of low intensity ( $M = 332.1$ ,  $SD = 66.44$ ), regardless of the age group.

Precondition 2 suggested that mean RTs to separated unimodal auditory stimuli A<sub>s</sub> were shorter than those to separated unimodal visual stimuli V<sub>s</sub>, irrespective of stimulus intensity and age group. Again, a Wilcoxon signed-rank test showed a significant difference between the RTs ( $T = -3.454$ ,  $p < 0.001$ ). Mean RTs to unimodal auditory stimuli A<sub>s</sub> ( $M = 349.46$ ,  $SD = 64.35$ ) were shorter compared to unimodal visual stimuli V<sub>s</sub> ( $M = 370.82$ ,  $SD = 43.06$ ; see **Fig.4**).



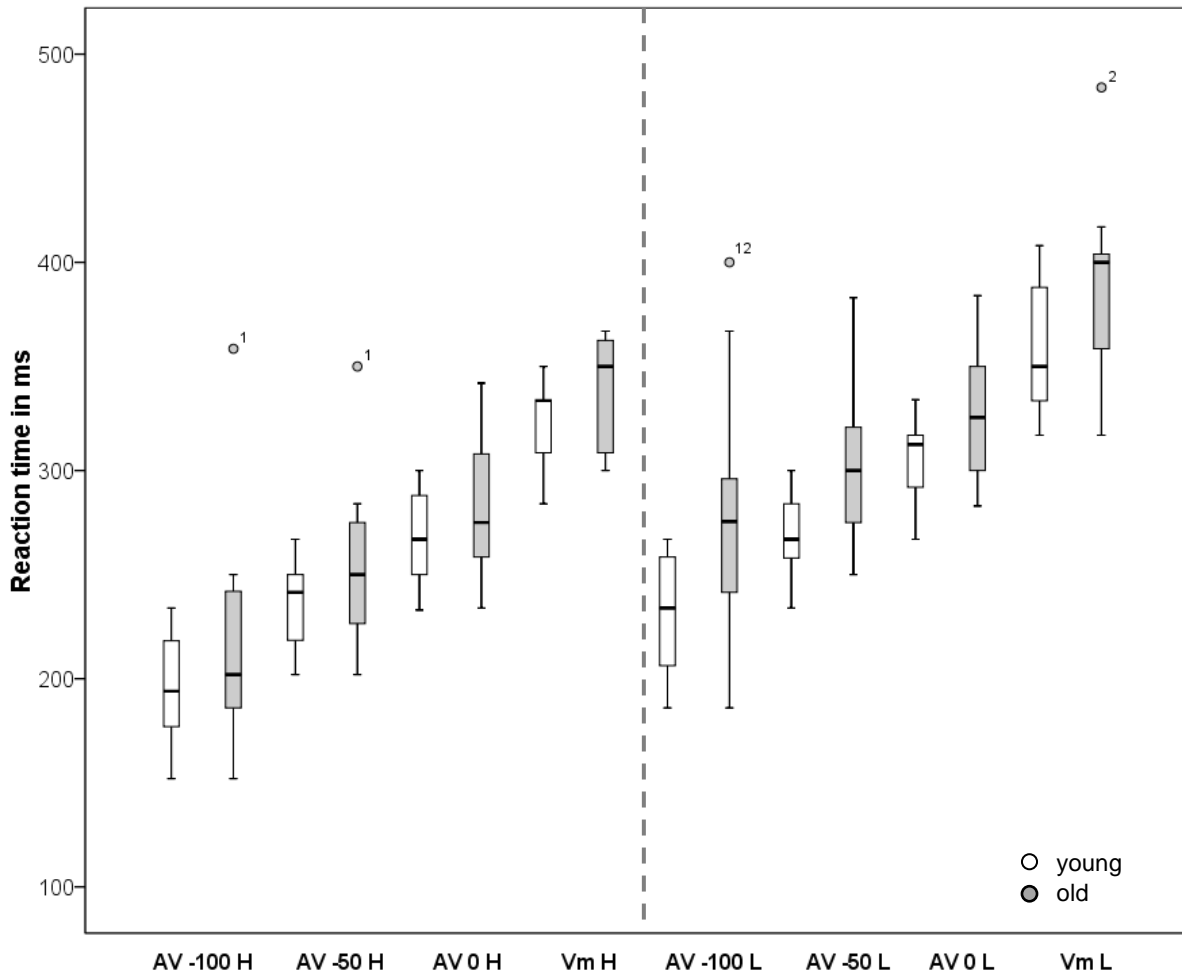
**Fig.4.** Effects of stimulus intensity and stimulus modality on RT. The box plots display the median, the first and the third quartile defining the box, and the 1.5 interquartile range of the lower and the upper quartile as whiskers. RTs are shown for the young (left) and old (right) age group. RT decreased with increasing stimulus intensity in both modalities and both age groups. RTs were faster for separated unimodal auditory stimuli ( $A_s$ ) as compared to separated unimodal visual stimuli ( $V_s$ ), consistent for both age groups.

Since both Precondition 1 and 2 supported shorter mean RTs to stimuli of high compared to low stimulus intensity and shorter mean RTs to unimodal auditory compared to unimodal visual stimuli, testing of the central hypotheses was pursued.

Four trend tests (Page) were conducted to probe whether the RTs followed a presumed trend in both age groups and for both stimulus intensities (Hypothesis 1). Due to the hypothesized ascending trend in the RTs from bimodal stimuli with an SOA of -100 ms to bimodal stimuli with an SOA of 0 ms and, finally, to mixed unimodal visual stimuli  $V_m$ , a four-stepped running index  $j$  for the trend test could be noted. Thus, for example, bimodal stimuli with an SOA of -100 ms received the index  $j = 1$ , whereas unimodal visual stimuli received the index  $j = 4$ . From Table J (see appendix; Bortz & Lienert, 2008) for  $n = 12$ ,  $k = 4$ , and  $\alpha = 0.01$ , a critical  $L$  value of  $L_{crit} = 324$  was taken. Thus, if  $L > L_{crit}$ , the null hypothesis could be rejected in favor of the alternative hypothesis  $H_{A1}$  (see 2.1.3). Due to the fact that four separate trend test were conducted,  $\alpha = 0.01$  was adjusted to  $\alpha^* = 0.0025$ . As a consequence, the following test would reveal significance whenever  $p < \alpha^*$ .

For the young age group, mean RTs to stimuli of low intensity followed the trend from audiovisual stimuli with an SOA of -100 ms to mixed unimodal visual stimuli  $V_m$  ( $L = 360$ ,  $z = 6.0$ ,  $p < 0.0001$ ) as well as mean RTs to stimuli of high intensity ( $L = 360$ ,  $z = 6.0$ ,  $p < 0.0001$ ). Mean RTs for the elderly age group pursued the presumed trend as well, for both low ( $L = 353.5$ ,  $z = 5.35$ ,  $p < 0.0001$ ) and high ( $L = 356$ ,  $z = 5.6$ ,  $p < 0.0001$ ) intensities. These results indicate that the mean RTs followed the trend expected by the alternative hypothesis  $H_{A1}$  within each age group and stimulus intensity. **Fig.5** illustrates the RTs to bimodal audiovisual stimuli and mixed unimodal visual stimuli  $V_m$ , for both intensities and

both age groups. RTs increased with declining stimulus intensity from bimodal stimuli with an SOA of -100 ms to those with no SOA and, finally, to mixed unimodal visual stimuli  $V_m$ , in both young and elderly age groups.



**Fig.5.** Effects of SOA and stimulus intensity on the RTs to bimodal audiovisual (AV) and mixed unimodal visual stimuli ( $V_m$ ) in young and elderly adults. The box plot displays the median, the first and the third quartile defining the box, and the 1.5 interquartile range of the lower and the upper quartile as whiskers. The left part of the figure illustrates RTs to stimuli of high intensity, whereas the right part of the figure illustrates RTs to stimuli low intensity. For both age groups and stimulus intensities, RTs increased along the predefined trend from bimodal stimuli with an SOA of -100 ms to unimodal visual stimuli  $V_m$  (Outlier: AV -100 H: subject 'S51', value: 358.5 ms; AV -50 H: subject 'S51', value: 350 ms; AV -100 L: subject 'S62', value: 400 ms; Vm L: subject 'S52', value: 484 ms).

In addition to Page's trend test, an ANOVA was conducted to investigate whether SOA or stimulus intensity had a general influence on the RTs between the two age groups. Across the two intensity levels, the mean RTs became faster with increasing stimulus intensity, as reflected by a significant main effect of the factor 'Stimulus Intensity' ( $F(1,22) = 155.55$ ,  $p < 0.001$ ). An additional main effect of 'SOA' ( $F(1,258) = 199.947$ ,  $p < 0.001$ , Greenhouse-Geisser corrected) was found, indicating that mean RTs decreased with increasingly negative SOAs. The interaction between the two main effects failed to reach significance ( $F(1,22) = 4.28$ ,  $p < 0.06$ ). Moreover, young and elderly adults were not significantly different

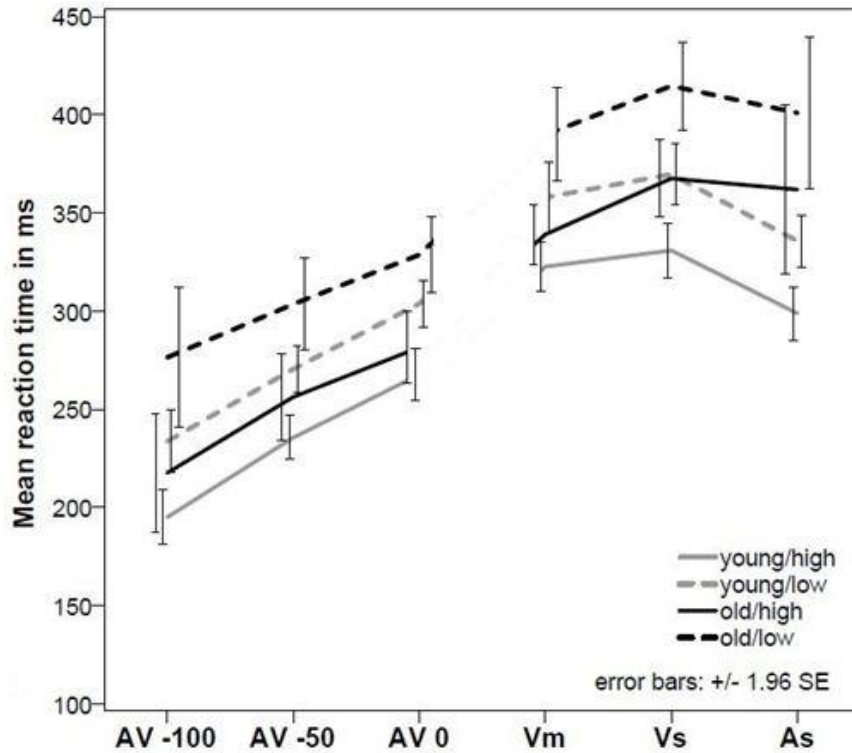


in their mean RTs to bimodal stimuli, suggested by the between-subject effect 'Age' ( $F(1,22) = 3.76, p < 0.07$ ).

In the next step of the analysis, Brunner's rank test was performed for the two factors 'Age' and 'Stimulus Intensity', to assess the effects of stimulus intensity and age on the RTs (Hypothesis 2). Table X (see appendix; Bortz & Lienert, 2008) contains critical z-values for  $\alpha = 0.05$  (one-tailed test). Thus, if  $|z| > z_{crit}$ , the null hypothesis could be rejected in favor of the alternative hypothesis. Due to the fact that six separate tests were conducted for each stimulus type,  $\alpha = 0.05$  was adjusted to  $\alpha^* = 0.0083$ . As a consequence, the following tests revealed significance whenever  $p < \alpha^*$ .

For the separated unimodal stimulus types  $A_s$  ( $z = -2.73, z_{crit} = 1.75, p < 0.007$ ) and  $V_s$  ( $z = -3.08, z_{crit} = 1.73, p < 0.003$ ), the test revealed significant differences for the main effect 'Age', meaning that young and elderly adults differed significantly in their RTs to separated unimodal auditory  $A_s$  and separated unimodal visual stimuli  $V_s$ . The main effect 'Age' failed to reach significance for mixed unimodal visual  $V_m$  as well as for all bimodal stimuli:  $V_m$  ( $z = -2.01, z_{crit} = 1.72, p = 0.04$ ),  $AV_{-100}$  ( $z = -1.57, z_{crit} = 1.73, p = 0.12$ ),  $AV_{-50}$  ( $z = -2.00, z_{crit} = 1.72, p = 0.05$ ), and  $AV_0$  ( $z = -1.46, z_{crit} = 1.72, p = 0.14$ ). Thus, the age groups did not distinguish themselves significantly in their reaction to mixed unimodal visual and bimodal audiovisual stimuli. In terms of the testing the main factor 'Age' the null hypothesis could be rejected in favor of  $H_{A2.1}$  (see 2.1.3) for both separated unimodal stimuli  $V_s$  and  $A_s$ .

The main effect 'Stimulus Intensity' became significant for all stimulus types, the bimodal stimulus types  $AV_{-100}$  ( $z = -10.62, z_{crit} = 1.73, p < 0.00001$ ),  $AV_{-50}$  ( $z = -11.94, z_{crit} = 1.73, p < 0.00001$ ),  $AV_0$  ( $z = -12.53, z_{crit} = 1.72, p < 0.00001$ ), as well as for the mixed and separated unimodal stimulus types  $V_m$  ( $z = -11.18, z_{crit} = 1.72, p < 0.00001$ ),  $A_s$  ( $z = -11.23, z_{crit} = 1.72, p < 0.00001$ ), and  $V_s$  ( $z = -7.05, z_{crit} = 1.73, p < 0.00001$ ). The null hypothesis could be rejected in favor of the alternative hypothesis  $H_{A2.2}$  (see 2.1.3) in all stimulus types, showing that RTs to stimuli of low intensities differed significantly from RTs to stimuli of high intensities in all stimulus types. **Fig.6** shows the RTs to stimuli of all tested stimulus types. Elderly adults showed slower mean RTs in all bimodal and unimodal stimulus types when compared to RTs of the young age group, but only RTs to the stimulus types  $A_s$  and  $V_s$  differed significantly between the age groups. For both age groups, RTs to stimuli of high intensities were faster than compared to RTs of low intensities, irrespectively of the stimulus type. Brunner's rank test revealed no interaction between the two main factors 'Age' and 'Stimulus Intensity', resulting in the assumption of the null hypothesis that no difference existed between the two main factors.



**Fig.6.** Effects of age and stimulus intensity on the RT. RTs are shown as means  $\pm$  1.96 standard errors (SE). RTs increased with age for both stimulus intensities, reaching from fastest RTs to bimodal stimuli with an SOA of -100 ms to slower RTs to unimodal stimuli. RTs to stimuli of high intensities were always faster than compared to stimuli of low intensities across both age groups.

### Multisensory response enhancement

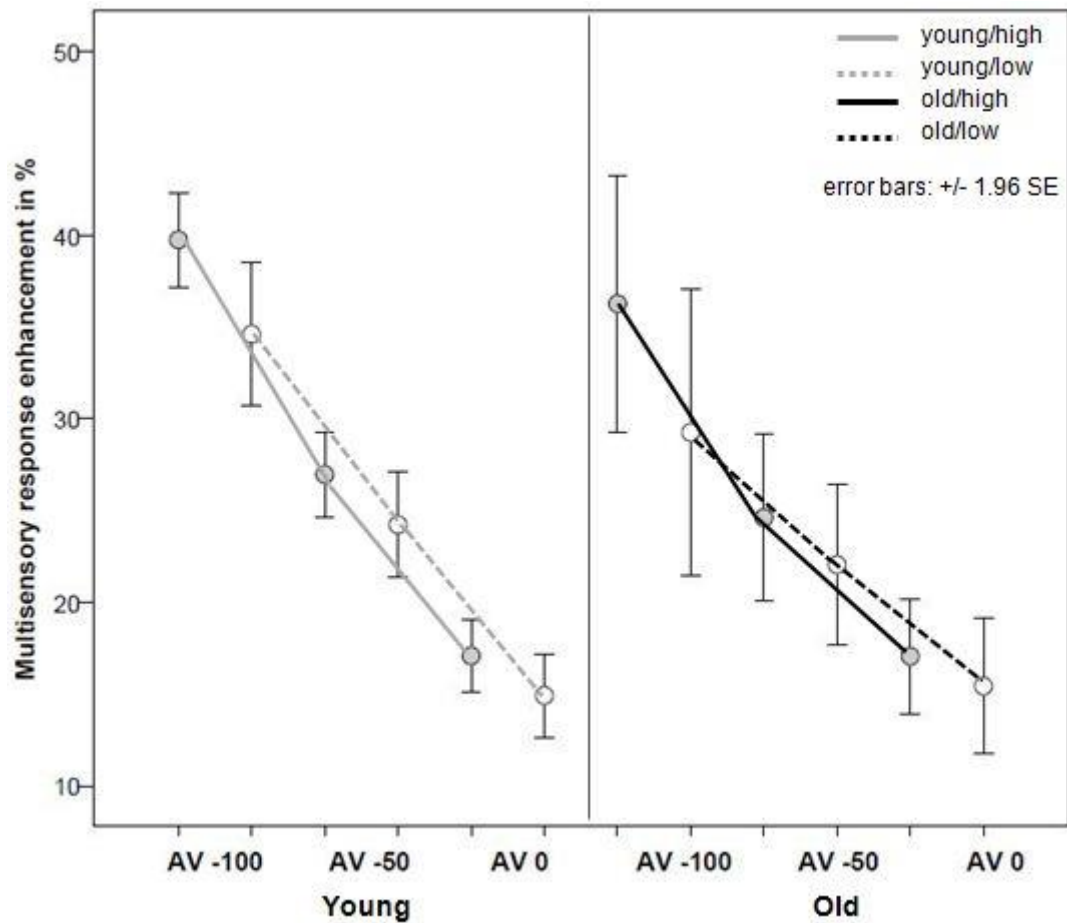
**Tab.3** shows MRE values (means and standard errors) calculated for each subject over the six bimodal stimulus types. For example, when RT to a bimodal stimulus was reduced by 5 % compared to the unimodal mean RT, this resulted in a MRE value of 5. The calculation resulted in positive MRE values (facilitation) in both age groups and for all bimodal stimulus types, with minimal MRE values for the young age group for bimodal stimuli with an SOA of 0 ms at low intensity ( $M = 14.92$ ,  $SD = 4.02$ ), and maximal MRE values for the same age group for bimodal stimuli with an SOA of -100 ms at high intensity ( $M = 39.74$ ,  $SD = 4.54$ ). Brunner's rank test was performed for the two within-subject factors 'Stimulus Intensity' and 'SOA' and the between-subject factor 'Age' (Hypothesis 3). Across the two intensity levels, MRE values increased with increasing stimulus intensity, as reflected by the significant main effect of the factor 'Stimulus Intensity' ( $F(1,22) = 14.67$ ,  $p < 0.03$ ; see **Fig.7**). The main effect of the factor 'SOA' reached significance ( $F(1,57) = 255.83$ ,  $p < 0.001$ ), corresponding to the notion that the amount of MRE increased from an SOA of 0 ms to an SOA of -50 ms and, finally, to an SOA of -100 ms. In terms of the testing of the main factors 'Stimulus Intensity' and 'SOA', the null hypotheses could be rejected in favor of the alternative hypotheses  $H_{A3.2}$

and  $H_{A3.3}$ , respectively. None of the interactions reached significance, resulting in the assumption of the null hypotheses that no difference existed between the factors.

However, comparing MRE values between the age groups, it can be seen that the amount of MRE is slightly higher for the young compared to the elderly, for nearly all stimulus types. But this observation could not be confirmed, because the main effect of the factor 'Age' failed to reach significance, resulting in assumption of the null hypothesis. The percentage of MRE differed between the age groups by 0.01 % at a high intensity bimodal stimulus with an SOA of 0 ms and by 5.34 % at a low intensity bimodal stimulus with an SOA of -100 ms. The only exception concerned the bimodal stimulus with an SOA of 0 ms at low intensity. Here, the elderly age group showed a slightly higher MRE value (0.51 %) as compared to the young age group.

**Tab.3.** Multisensory response enhancement (mean  $\pm$  standard error, in %) for all bimodal stimuli, stimulus intensities, and stimulus onset asynchronies (SOAs), sorted by age group (for young and old:  $n = 12$ ).

Intensity	Age	SOA		
		AV <sub>-100</sub>	AV <sub>-50</sub>	AV <sub>0</sub>
high	young	39.73 $\pm$ 1.31	26.95 $\pm$ 1.19	17.08 $\pm$ 0.99
	old	36.26 $\pm$ 3.56	24.60 $\pm$ 2.32	17.06 $\pm$ 1.59
low	young	34.59 $\pm$ 1.99	24.22 $\pm$ 1.47	14.92 $\pm$ 1.16
	old	29.25 $\pm$ 3.96	22.04 $\pm$ 2.25	15.43 $\pm$ 1.89



**Fig.7.** Multisensory response enhancement (MRE) for all bimodal stimuli. MRE (in %) is shown as mean  $\pm$  1.96 standard error (SE) for the young (left) and the elderly (right) adults. MRE increased with increasing stimulus onset asynchrony (SOA) for all bimodal stimulus types. For stimuli of low intensities, MRE was smaller when compared to stimuli of high intensities of the same stimulus type. Young adults showed a slightly higher, but not significant, MRE as compared to elderly adults in nearly all stimulus types.

### 2.3. Discussion

This study was designed to investigate age-related differences in mean RTs to unimodal visual, unimodal auditory, and bimodal audiovisual stimuli with varying stimulus intensities and SOAs. To assess this issue, a FAP task with visual target was used. The results showed that, for both young and elderly adults, RTs decline from unimodal to bimodal stimuli, whereby RTs were slowest for bimodal stimuli with large SOA. While the age groups did not differ in their responses to bimodal stimuli, RTs varied for unimodal stimuli. Contrary to the hypothesis, the present results did not reveal age-related differences in the multisensory response enhancement.

The study is based on two common empirical observations. First, RTs to high intensity stimuli are faster than RTs to low intensity stimuli. Our results confirm this observation and are thus in line with the previous literature. It is well known that RT usually decreases with increasing stimulus intensity (Adams & Behar, 1966; Behar & Adams, 1966; Kohfeld, 1971). Many previous studies found faster response times for high intensity stimuli as compared to low intensity stimuli for unimodal visual (Bell et al., 2006; Rach et al., 2011; Senkowski et al., 2011), auditory (Diederich & Colonius, 2004a; Rach et al., 2011; Senkowski et al., 2011; Ulrich et al., 1998), tactile (Diederich & Colonius, 2004), and bimodal audiovisual stimuli (Rach et al., 2011; Senkowski et al., 2011).

Second, RTs are found to be shorter for unimodal auditory than for unimodal visual stimuli. This was replicated in the present data, thus in line with Diederich and Colonius (2004) demonstrating shorter RTs to unimodal auditory stimuli in a RTP task. Their results showed that mean RT to visual stimuli was always slower than to auditory stimuli, regardless of the intensity level of the auditory stimulus. Furthermore, Gielen et al. (1983) already indicated RTs to unimodal visual stimuli to be 24 ms longer than for unimodal auditory stimuli. Whereas the translation of physical energy into a neural signal is conducted by mechanoreceptors in both audition and somatosensation, in vision a photochemical transduction must be performed (Bell et al., 2006). Shorter response onset latencies of neural responses in the auditory and somatosensory system compared to the visual system are seen as a direct result of these different types of transduction (Wallace et al., 1996). Hence, both observations were confirmed, suggesting that the data are in line with previous studies. The main question in this study was if, and to which extent, young and elderly adults differ in their responses to various stimulus types.

We found that mean RTs increased from bimodal stimuli with a large SOA to bimodal stimuli with a small SOA and, finally, to unimodal visual stimuli. This trend is consistent across both age groups and stimulus intensities. The effect when RT to an unimodal stimuli

tends to be faster when a stimulus of another modality is presented in a close temporal and spatial alignment, is known as intersensory facilitation effect (Hershenson, 1962) or redundant target effect (e.g. Miller, 1982). In the present study this effect of intersensory facilitation was confirmed, which is in line with many other studies, which proved this effect as robust. Either when participants were instructed to respond to any perceived stimulus (RTP task; Diederich & Colonius, 1987; Gielen et al., 1983; Hershenson, 1962; Miller, 1982; Peiffer et al., 2007; Senkowski et al., 2011) or when they were instructed to perform a FAP task and to respond only to a target modality (Bernstein et al., 1969; Diederich et al., 2008; Morrell, 1968; Rach & Diederich, 2006), faster RTs were always found to bimodal relative to unimodal stimuli. Concerted with the present results, Diederich et al. (2008) revealed the same trend of decreasing RTs with increasing SOAs in their FAP task. The SOA determines the amount of RT reduction, while the amount being maximal for bimodal stimuli in which the SOA is closest to the difference in unimodal RTs (Diederich & Colonius, 2004a). In addition, this facilitation effect in RTs to multisensory stimuli has been observed for both young and elderly adults (Laurienti et al., 2006).

Turning to possible neurophysiological underpinnings of these effects, the observed speed-up in RTs to bimodal compared to unimodal stimuli may be attributed to the existence of bimodal neurons. Afferent visual, somatosensory, and auditory information are integrated by single neurons in the mammalian superior colliculus (SC; cat; Driver & Spence, 2000; Stein & Meredith, 1993; Wallace et al., 1993). About half of these cells respond to sensory information from more than one sensory modality (Meredith & Stein, 1986a) and are involved in producing initial saccadic and manual responses (Stein, 2012). According to Kadunce et al. (2001), neurons in the SC have receptive fields for each modality they respond to, and these receptive fields are largely in spatial register (Driver & Spence, 2000; Meredith & Stein, 1986a, 1986b). Thus, neurons that represent the same region in space (e.g. the peripheral region) have overlapping receptive fields (Meredith & Stein, 1996). The size of the overlapping region of the receptive fields varies across multisensory SC neurons (Kadunce et al., 2001). Kadunce et al. (2001) found that the region most responsive in a multisensory neuron is the region of overlapping receptive fields. Because of the fact that a unimodal stimulus can elicit a response of a bimodal neuron as well, the faster response to a bimodal stimulus must be due to response facilitation of the bimodal neuron to the combination of two unimodal stimuli (Diederich & Colonius, 2004a). Spatial and temporal alignments of the unimodal stimuli modulate the amount of the enhanced response to the bimodal stimulus as well as the stimulus intensities (Rach et al., 2011). Whenever an enhanced response is observed, a large number of neurons is involved in creating this response (Diederich & Colonius, 2004a).

In respect to differences between the age groups, the present study obtained differences in the RTs to unimodal auditory and unimodal visual stimuli, but no differences were found in RTs to bimodal stimuli. Elderly adults had longer RTs relative to young adults in both unimodal stimulus types. Our results are in line with former studies regarding the point that both age groups differ in their RTs to unimodal stimuli. Some previous studies showed age-related differences in RTs in all stimulus types, whereas others did not.

Generally, most studies obtained longer RTs for the elderly compared to the young age group (Alain et al., 1996; West & Alain, 2000; West & Baylis, 1998). Studies by Hugenschmidt et al. (2009) and Laurienti et al. (2006) revealed slower RTs for the elderly group than for the young group in both unimodal and bimodal stimulus types. Diederich et al. (2008) observed crossmodal audiovisual interaction effects in a FAP task in young and elderly adults. Again, elderly adults were slower under all stimulus types. For example, Diederich et al. (2008) found saccadic eye-movement to the unimodal visual stimulus much slower for the elderly than for the young adults (295 ms vs. 171 ms, respectively). In addition, Stephen et al. (2010) also exhibited larger RTs for the elderly adults in all stimulus types.

In contrast, Peiffer et al. (2007) did not find an age effect for unimodal stimuli in their RTP task. Whereas both age groups showed similar RTs to unimodal stimuli, the elderly tended to respond faster to bimodal stimuli than the young adults. In the current study, the lack of age-related changes in RT to bimodal stimuli suggests that elderly adults have a different response criterion or use different cognitive strategies than young adults.

The discrepancy between the results reported in the literature and the present results may be related to task difficulty. In the present study, simple unimodal visual (Gabor patches), unimodal auditory (pure tones), and bimodal stimuli were used for stimulus presentation. As opposed to this, most studies showing an increase in the RT for elderly adults used more complex and demanding tasks than those used here. For example, Laurienti et al. (2006) instructed their participants in a two-alternative forced-choice discrimination task to discriminate between the colours red and blue presented as visual (coloured discs), auditory (verbalization of the colour) or bimodal stimuli. Their participants had to press either the button under their index finger, whenever they receive the colour blue or to press the button under their middle finger, whenever they receive the colour red. In comparison, Stephen et al. (2010) tested the effect of age with realistic temporal delays for near and far sources in a perspective drawing of a soccer field with visual (near/far presentation of a soccer ball), auditory (quiet/loud tone corresponding to the proximity) and bimodal stimuli. They instructed their participants to respond as fast as possible with a button press when stimuli were near or far, relative to themselves.

Several factors that are independent of multisensory integration can affect RT differences between young and elderly adults (Laurienti et al., 2006). As Diederich et al. (2008) note, it remains unclear whether the observed slowing to unimodal stimuli by the elderly is due to an age-related decline in processing visual or auditory stimuli or to a more centrally located processing stage where visual and auditory information are integrated. In elderly adults, mean peripheral processing times were longer for visual and auditory stimuli as compared to young adults (young: 48 ms for the visual and 18 ms for the auditory stimulus; elderly: 84 ms for the visual and 98 ms for the auditory stimulus; Diederich et al., 2008). A general cognitive decline including the reduction in processing speed (Salthouse, 1996), processing capacity (Lavie, 1995), and inhibitory functions (Hasher & Zacks, 1988; Healey et al., 2008) is thought to be responsible for longer RTs with increasing age. According to Laurienti and Hugenschmidt (2012), each of these explanations has strengths and weaknesses. Failed processing and disruption in sequential processing (Cerella, 1991, 1985; Salthouse, 1996; Verhaeghen & Cerella, 2002) are thought to be a direct result from a decreased overall processing speed. Another characteristic standing for age-related cognitive impairment is a reduced inhibitory processing (Hasher & Zacks, 1988). Alain and Woods (1999), as well as other studies, demonstrated that elderly adults have a decreased capability to suppress background information across sensory modalities in comparison to young adults (Amenedo & Díaz, 1998; Poliakoff et al., 2006). Because of the fact that this decreased ability is thought to be related to a reduced inhibitory control, a proportion of cognitive changes with age may be attributed to this. It is possible that elderly adults have deficits in their attention, and stimuli within or across sensory modalities distract them more (Alain & Woods, 1999; Andrés et al., 2006; Healey et al., 2008; Mozolic et al., 2012; Poliakoff et al., 2006; West & Alain, 2000; Yang & Hasher, 2007).

The aforementioned age-related changes may explain the differences in the response to unimodal stimuli in the present study. But some former studies showed that elderly adults can perform as good as their young counterparts (Looren de Jong et al., 1989; Peiffer et al., 2007; Yordanova et al., 2004) when the conditions are correctly defined. In a more complex experimental design (Laurienti et al., 2006; Stephen et al., 2010), where participants have to discriminate between different stimulus characteristics, the RT might be more influenced by a cognitive component than in an experiment, in which participants only have to respond to a predefined target modality (present study). This may explain why the present results showed an age-related difference in the response to unimodal stimuli, but did not reveal an age-related difference in the reaction to bimodal stimuli.

MRE is demonstrated by the percentage of speed-up in the response to bimodal compared to unimodal visual stimuli. In the present study, both young and elderly adults showed an enhancement in their response to multisensory as compared to unimodal stimuli.



Contrary to the hypothesis, the age groups did not differ in their amount of MRE, which is not consistent with the results of former studies in the field of multisensory integration in aging. Laurienti et al. (2006) were the first to show that the elderly can benefit more than the younger from the combination of information from multiple sensory modalities. Further studies supported this observation (Diederich et al., 2008; Hugenschmidt et al., 2009; Peiffer et al., 2007). They showed a higher amount of interaction for the elderly adults, indicating that multisensory information increases the response of elderly adults more than those of young adults. This benefit was observed in studies using saccadic eye-movements (Diederich et al., 2008) and in studies using manual responses (Laurienti et al., 2006). More precisely, Laurienti and Hugenschmidt (2012) concluded, with respect to prior studies that have investigated the MRE with aging (Diederich et al., 2008; Hugenschmidt et al., 2009; Laurienti et al., 2006; Peiffer et al., 2007), that the amount of interaction is about 50-100 % higher in the elderly age group relative to the young age group.

In contrast, the present results obtained a similar amount of MRE for both age groups, indicating that elderly adults did not benefit more from the presentation of bimodal stimuli than young adults. Stephen et al. (2010) found faster RTs to bimodal stimuli than to unimodal stimuli in their MEG study, but for the elderly age group no facilitation effect in RTs to bimodal stimuli was observed. Moreover, the young age group showed higher response enhancement in the presence of bimodal stimuli. Thus, our finding is consistent with the results of Stephen et al. (2010), indicating that elderly adults did not benefit more from a bimodal stimulus than young adults.

One possible explanation for such conflicting results was suggested by Freiherr et al. (2013), who attributed this to the use of different multisensory testing and data analysis techniques. In addition, Laurienti et al. (2006) suggested that large differences in the design of experimental tasks could be responsible for the conflicting results. A lot of studies in the field of multisensory integration used stimuli at or just above the perceptual threshold, because these stimuli are more likely thought to be integrated (Calvert et al., 2004) and to elicit greater response enhancements (Stanford & Stein, 2007). However, none of the stimuli used in the present study was at or just above perceptual threshold, similar to a daily life situation where most stimuli are usually not close to the perceptual threshold. Stephen et al. (2010) concluded from the results of Stanford et al. (2005) that simple linear summation or suppression could be the result of multisensory interaction if the stimuli are not close to the threshold. Thus, a larger response enhancement in elderly adults might be elicited through near-threshold stimuli. These weaker stimuli may thus follow the rule of inverse effectiveness (Stein & Meredith, 1993). According to Diederich et al. (2008), stimuli of high intensity could have an advantageous influence on multisensory integration in the elderly age group. But one drawback of high intensity stimuli might be that the advantage of inverse effectiveness is

lost given that the elderly could detect the stimuli without any problems (Stephen et al., 2010).

Diederich and Colonius have proposed the time-window-of-integration (TWIN) model (Colonius & Diederich, 2004; Diederich & Colonius, 2004b) for crossmodal response enhancement in both RTP and FAP tasks. Recently reported by Kandil et al. (2014) in a parameter recovery study, it has been shown that the parameter estimates (duration of the unimodal visual and auditory first stage, duration of the integrated second stage, width of the time window, and the effect size) of the TWIN model are highly accurate and precise, resulting in a high reliability and criterion validity of the process. The TWIN model may help to explain the current results. Diederich et al. (2008) tested with their TWIN model at which stage multisensory processing differs between young and elderly adults. The model distinguishes between two serial processing stages of the entire (saccadic) RT (Diederich & Colonius, 2004b). The first is a peripheral stage, a race between the visual and the auditory stimuli, whereas the second stage consists of converging subprocesses of multisensory integration and preparation of a response. They suggest that in a “[...] focused attention situation, the window of integration is ‘opened’ only by activity triggered by the non-target stimulus” (Diederich & Colonius, 2004b), meaning that “[...] crossmodal integration is effective only if the non-target stimulus wins the race in the first stage” (Diederich & Colonius, 2004b). When the target stimulus falls into a given time window of constant duration, crossmodal interaction will be elicited (Diederich & Colonius, 2004b). When the target stimulus wins the race in the first stage, no crossmodal interaction takes place (Diederich et al., 2008). According to Diederich and colleagues (Diederich et al., 2008; Diederich & Colonius, 2004b), the window of integration can be seen as kind of a filter. It defines if stimuli of various modalities (e.g. visual and auditory) are perceived close enough in time for successful crossmodal interaction. Diederich et al. (2008) found a greater width of the time window for the elderly compared to the young age group, consistent with the conclusion of Laurienti et al. (2006). The width of the time window for the young and the elderly age group resulted in 275 and 450 ms, respectively (Diederich et al., 2008). Although the elderly have a broader time window, the probability of integration is smaller due to slower peripheral processing times (Diederich et al., 2008). Moreover, the probability of integration could be smaller due to more variability in sensory timing (Diederich et al., 2008). This helps to explain the present results showing that the elderly adults did not benefit more from the presentation of bimodal stimuli in comparison to the young adults.

The mechanisms underlying enhanced or degraded multisensory integration in the elderly relative to the young age group remain unclear. One may think that elderly adults rely more on the combined information from several sensory modalities because of degraded unisensory processing (DeLoss et al., 2013). Higher temporal discrimination thresholds

(Humes et al., 2009) or a decline in sensory function (Bozian & Clark, 1980; Corso, 1971; Nusbaum, 1999) could be responsible for the altered multisensory integration performance, as well as a decline in sensory acuity in peripheral sensory modalities (Owsley, 2011) or a more general cognitive slowing (Salthouse, 1996). But Diederich et al. (2008) concluded from their TWIN model that altered multisensory integration in the elderly is a direct result of the slowing of peripheral processing. In elderly adults, the probability that processing of both auditory and visual stimulus falls into the time window, is reduced due to prolonged RTs and an increase in response variability. Thus, a broadened time window can only in part compensate for a reduced probability that multisensory integration will occur (Diederich et al., 2008).

Results of the present study revealed that multisensory integration, as measured by MRE, is greatest with large SOA between the visual and the auditory stimulus. This is in line with Colonius and Diederich (2004) finding mean RT monotonically decreasing as a function of SOA (over a certain range) in a FAP task with visual target: The earlier the non-target stimulus was presented relative to the target, the larger is the multisensory integration effect. As Colonius and Diederich (2004) detailed, for SOAs maximizing the overlap of the unimodal RT distribution, multisensory interaction is greatest. In addition to SOA, the level of the stimulus intensity can affect the amount of MRE as well. It is well known that combining two unimodal stimuli at low intensity results in maximal multisensory interaction (inverse effectiveness), while the amount of multisensory interaction reduces when the intensity level of the stimuli is increased (Hairston et al., 2003; Stein et al., 1996; Wallace et al., 1996).

The amount of MRE was found to increase with stimulus intensity. This increase was obtained for young and elderly adults as well as for each SOA. Opposing effects were reported in the literature. For example, Diederich and Colonius (2004a) found higher MRE for bimodal stimuli of lower stimulus intensity in their RTP task. Their results follow thus the principle of inverse effectiveness where smaller unimodal responses from low intensities are associated with higher amounts of multisensory interaction (Hairston et al., 2003; Meredith & Stein, 1986a; Stein et al., 1996; Wallace et al., 1996). Studies of Rach et al. (2011) and Senkowski et al. (2011) showed the same effect of inverse effectiveness in MRE. However, the current results are in line with Arndt and Colonius (2003), Frens et al. (1995), and Hughes et al. (1994), who failed to demonstrate an enhancement in the response to multisensory stimuli of low stimulus intensity when compared to high stimulus intensity.

Several causes may be responsible for these conflicting results. Corneil et al. (2002) suggested that, in earlier studies, the low intensity stimuli were not close enough to the perceptual threshold. This holds for the present study where none of the used stimuli was close to perceptual threshold and may explain the lack of inverse effectiveness. Stimuli that

are close to perceptual threshold are more likely to be integrated than more intense stimuli (Calvert et al., 2004). Imagine a situation where the combination of two or more unimodal stimuli of low intensity near the perceptual threshold form a warning signal, which is thus above the perceptual threshold. For an animal in a predator-prey-situation this example of inverse effectiveness would be most important (Diederich & Colonius, 2004a). Thus, this could be one explanation why inverse effectiveness was not found in most of the human studies (Diederich & Colonius, 2004a). Another suggestion regarding the lack of inverse effectiveness in MRE was made by Corneil et al. (2002). They argued that many previous studies, as well as the present study, contained a FAP task, which perhaps results in longer RTs due to participants having to discriminate between the target and the non-target. In their RTP task, unimodal visual, unimodal auditory, and bimodal audiovisual stimuli were presented with audiovisual background noise. With enhanced signal-to-noise ratio they found decreasing MRE, as predicted by inverse effectiveness. When participants were instructed to perform a FAP task and to respond only to stimuli of a target modality, the inverse effectiveness was shown to depend only on the intensity of the target stimulus (Rach et al., 2011; Rach & Diederich, 2006). Moreover, Colonius and Diederich (2012) showed that, within the TWIN framework, the amount of MRE in a RTP task is at least as large as in a FAP task, but the probability of multisensory integration in a RTP task is twice as large as in a FAP task. Furthermore, they found that for increasing the rate of the exponential distribution for the peripheral processing times of the unimodal stimuli, MRE decreases in RTP tasks, whereas MRE increases in FAP tasks. Colonius and Diederich (2012) reported that, in a RTP task, the prediction of their TWIN model is consistent with the principle of inverse effectiveness, stating higher crossmodal facilitation with stimuli close to perceptual threshold (Meredith & Stein, 1986a). In contrast, the prediction of their TWIN model is not stable in case of a FAP task. Assuming that the TWIN model is underlying our data, this would help to explain the lack of inverse effectiveness in the present study.

To conclude, the results of this study suggest that young and elderly adults do not differ as much in their multisensory integration as observed in the literature. Investigations in the field of multisensory integration in the elderly implied that previous reported changes in the performance could be due to changes in selective attention (Alain & Woods, 1999) and crossmodal perception (Andrés et al., 2006; Poliakoff et al., 2006), as well as an age-related and more systematic decrease in the perception of unimodal stimuli (McGovern et al., 2014). It is important to understand how alterations in the peripheral processing interact with changes in the multisensory processing. Thus, further studies with stimuli at or near the perceptual threshold are needed to determine the contribution of decreased peripheral processing to multisensory integration in the elderly.

### 3. Experiment 2: EEG experiment based on Senkowski et al. (2011)

The main purpose for the second experiment was to conduct a study, which is the first investigating age-related changes in multisensory integration mechanisms with an electrophysiological approach. To this end, we decided to replicate the EEG study by Senkowski et al. (2011) examining audiovisual integration and extended it to the notion that two age-groups (a young and an elderly) were tested instead of one. Stimuli and procedure in the present experiment were much the same as used by Senkowski et al. (2011). Unimodal auditory, unimodal visual, and bimodal audiovisual stimuli presented at low, middle, and high intensity were used to investigate possible differences in audiovisual integration in young and elderly adults. Based on the results by Senkowski and colleagues (2011), two hypotheses could be generated.

**Hypothesis 4** is based on the study by Senkowski et al. (2011), where early multisensory interactions occurred most robustly when the presented stimuli were low in intensity. Hypothesis 4 claims that the amount of audiovisual interaction (MI) is most robust when stimuli are presented at low stimulus intensity, i.e.:

$$MI_{\text{low}} > MI_{\text{high}}.$$

**Hypothesis 5** is based on SRT and RT studies by Diederich et al. (2008), Laurienti et al. (2006), and Stephen et al. (2010), showing slower SRTs and RTs compared to young adults. In line with these RT results, Hypothesis 5 suggests that audiovisual interaction (MI) occurs later in time (t) in the elderly as compared to the young age group:

$$t(MI_{\text{old}}) > t(MI_{\text{young}}).$$

#### 3.1. Materials and methods

##### 3.1.1. Participants

Twenty-four paid adults participated in the present study. The twelve young (aged 18-26 years,  $M = 20.75$ ,  $SD = 2.60$ , ten female) and twelve elderly adults (aged 66-70 years,  $M = 67.92$ ,  $SD = 1.38$ , twelve female), who were different from the participants in Experiment 1, reported normal hearing and had normal or corrected-to-normal vision. Young adults were students at the Jacobs University Bremen, whereas the elderly adults were recruited from a pool of participants, who had registered for a former experiment at the Jacobs University Bremen. Participants provided a written informed consent and agreed with the anonymous storage, analysis, and publication of the data. For an expense allowance participants received 9 € per hour and a single flat rate for travel expense of 5 €. The

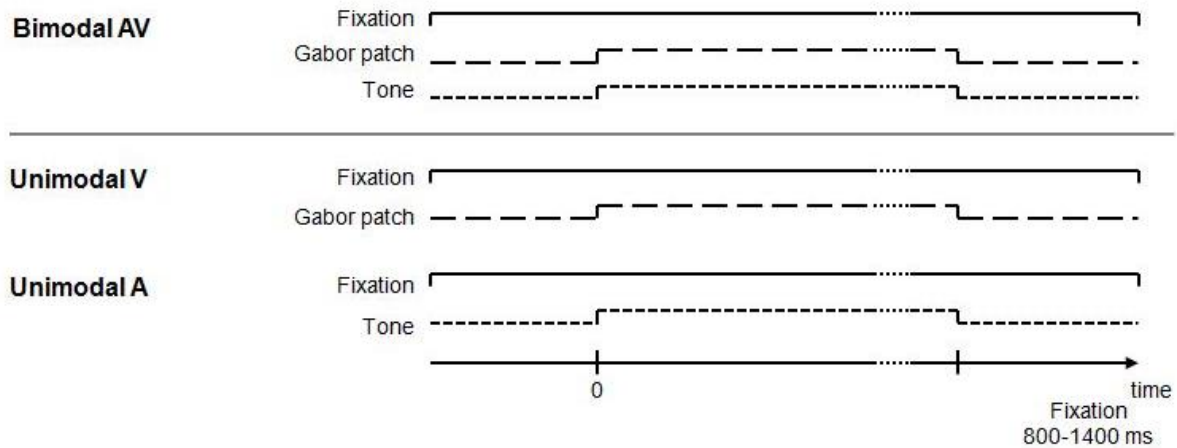
experiment was conducted according to the principles expressed in the Declaration of Helsinki (1964).

### 3.1.2. Procedure and stimulus conditions

The experiment was conducted in a darkened but not electrostatically shielded room at the Jacobs University Bremen. Participants were seated 57 cm apart from a monitor and were instructed to fixate a fixation point (a white cross), which was visible at the center of the monitor during the whole experiment.

Participants received a randomized stream of unimodal auditory (A), unimodal visual (V), and bimodal audiovisual (AV) stimuli. All stimulus types were presented at low, middle, and high intensities. During the experiment, participants were instructed to fixate the fixation point with no demand for a manual response. Their eye movements were controlled via electrooculogram (EOG).

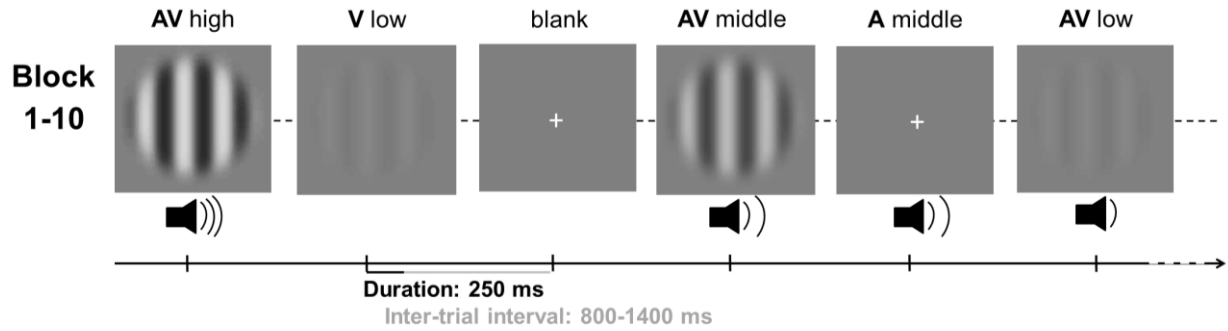
Stimuli and experimental design of this study were based on Senkowski et al. (2011). **Fig.8** illustrates the time course of the single unimodal and bimodal trials. Visual stimuli consisted of Gabor patches, which match and activate the shape of the receptive fields in the visual cortex efficiently (Daugman, 1980). Gabor patches with vertical gratings (spatial frequency = 1 cycle/degree; Gaussian standard deviation = 1.5) were presented at the center of the 19" computer monitor. Stimuli had a mean luminance constant at a level of 20 cd/m<sup>2</sup>. Michelson contrast ( $((\text{maximal luminance} - \text{minimal luminance}) / (\text{maximal luminance} + \text{minimal luminance})) * 100 \%$ ) of low, middle, and high intensities was 10 %, 50 %, and 90 %, respectively. Auditory stimuli consisted of pure tones with a frequency of 1000 Hz, which were presented via two external stereo speakers placed to the left and to the right of the monitor. Auditory stimuli comprised of low, middle, and high intensities with sound-pressure levels of 40, 55, and 70 dB, respectively. Bimodal audiovisual stimuli consisted of corresponding combined unimodal stimuli of the same intensity level (low A + low V = low AV, middle A + middle V = middle AV, and high A + high V = high AV) and were presented with the same onset (no SOA). With a rate of 32.2 %, non-stimulus events (blanks) were intermixed into the stream of uni- and bimodal stimuli.



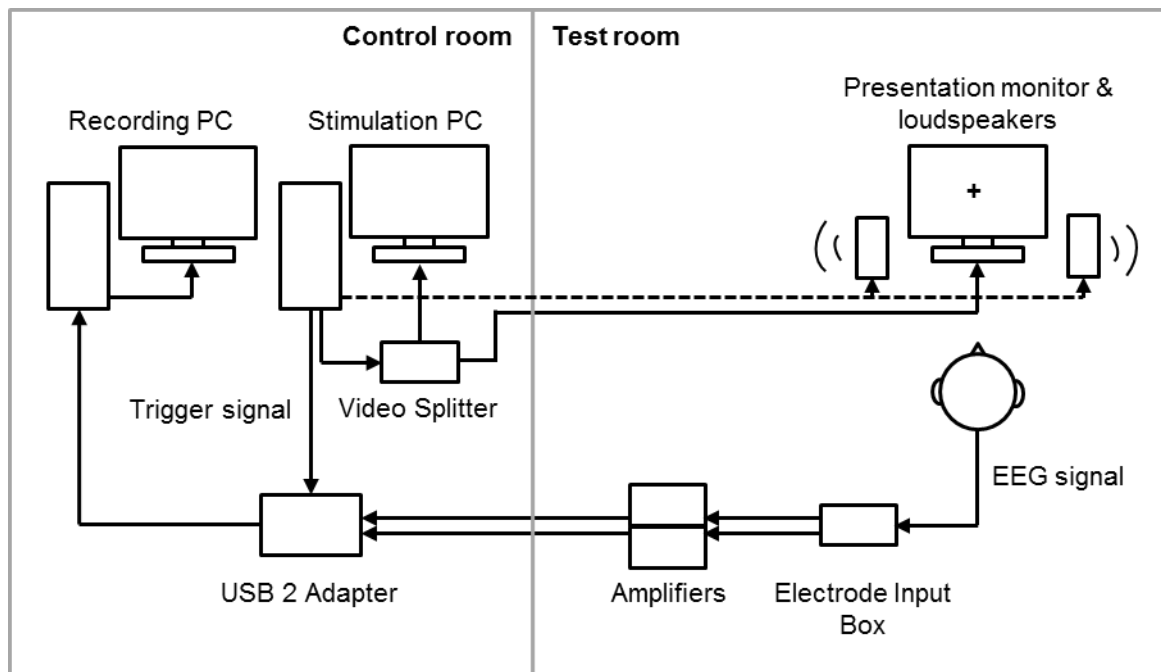
**Fig.8.** Time course of a single trial. The fixation was visible during the whole experiment. *Top:* Time course for a bimodal audiovisual stimulus. The auditory (dotted) and the visual stimulus (dashed) started with the same onset. *Bottom:* Time course for unimodal visual (V) and unimodal auditory (A) stimuli.

All unimodal (A, V) and bimodal (AV) stimuli were presented for 250 ms (for auditory stimuli (A, AV): 10 ms rise and fall times). The entire session was divided into ten blocks of about 4 minutes (199 trials in each block) of duration each. The nine stimulus types (A low, A middle, A high, V low, V middle, V high, AV low, AV middle, AV high) were offered in random order with equal frequencies of 150 trials. Blanks were intermixed with a frequency of 640 trials. The inter-trial interval varied randomly between 800 and 1400 ms.

**Fig.9** illustrates an exemplary experimental setup and **Fig.10** displays an exemplary schematic setup of the EEG laboratory. Stimuli were presented by a stimulation PC with Linux operating system (Ubuntu 14.04 LTS). The monitor was driven through a AMD Radeon HD 7470 OEM video card. A Video Splitter (Aten International Co., Ltd., New Taipei City, Taiwan) divided the video signal of the stimulation PC in order to receive the same signal on both the control and the presentation monitor. A custom-written C program (Dennis Ritchie & Bell Labs, Murray Hill, NJ, USA) using the OpenGL (Khronos Group Inc., Beaverton, OR, USA) and the OpenAL (Creative Technology Ltd., Singapore) libraries controlled the stimulus presentation. The exact timing between visual and acoustical stimulation was adjusted to the millisecond level using an oscilloscope equipped with custom-built photo LEDs and a microphone. The EEG signal was passed through an Electrode Input Box (Brain Products GmbH, Gilching, Germany) and two amplifiers to a USB 2 adapter (Brain Products GmbH, Gilching, Germany). Together with the trigger and the pattern signal, submitted by the stimulation PC, the EEG signal was transmitted to the EEG recording PC with Windows operating system (Windows 7). BrainVision Recorder (Brain Products GmbH, Gilching, Germany) was used for recording the EEG and saving it for later off-line analysis.



**Fig.9.** Exemplary experimental setup of the EEG experiment based on Senkowski et al. (2011). Participants were presented with a randomized stream of unimodal auditory (A), unimodal visual (V), and bimodal audiovisual (AV) stimuli of low, middle, and high intensity. Blanks were intermixed during all blocks. Participants were instructed to fixate the fixation point with no demand for a manual response.



**Fig.10.** Exemplary schematic setup of the EEG laboratory. The stimulus presentation and EEG recording took place in the control room (left), whereas the participant sat in the test room (right). Presentation monitor and loudspeakers in the test room were controlled through the stimulation PC. During the experiment, participants sat in front of the monitor and fixated a fixation cross. Continuous EEG was acquired from 25 active scalp electrodes, which were connected to an Electrode Input Box and forwarded through two amplifiers to an USB 2 adapter. Together with the trigger and pattern signal from the stimulation PC, the EEG signal was transferred to the recording PC.

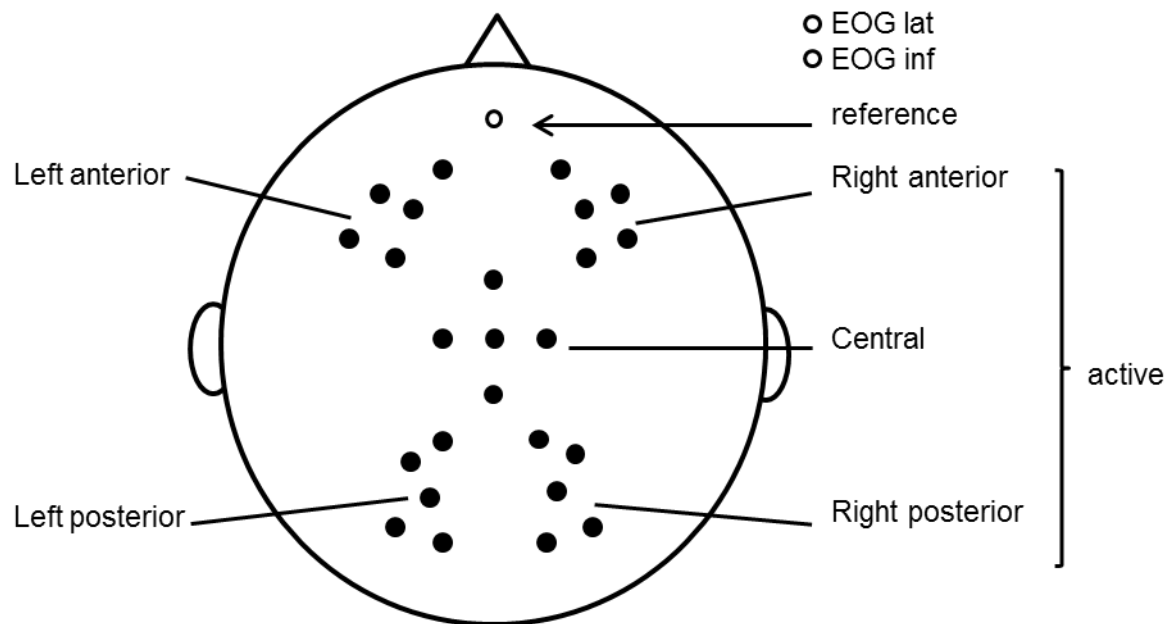
### 3.1.3. EEG data acquisition and analysis of event-related potentials

Continuous EEG was acquired from 25 active scalp electrodes (Ag/AgCl sintered ring electrodes), which were mounted into an elastic cap (EASYCAP GmbH, Herrsching, Germany), versus a reference electrode at FPz. Scalp electrodes were placed at AF3, AF4,



F3, F4, F5, F6, FCz, FCL, FCR, FC3, FC4, Cz, C1, C2, CPz, P1, P2, P3, P4, PO3, PO4, O1, O2, PO7, and PO8, according to the International 10-20 System (see **Fig.11**). Abralyt 2000 (EASYCAP GmbH, Herrsching) was used as a chloride-free, abrasive electrolyte gel during the recordings. The sampling rate was 500 Hz; the band-pass filter was set from 0.1 to 166 Hz. In addition, a 50 Hz low-pass filter was used. Horizontal and vertical eye movements were measured with two electrooculogram (EOG) electrodes placed lateral and inferior to the participant's right eye, respectively. EEGLAB (Swartz Center for Computational Neuroscience, San Diego, USA, version v12.0.2.3b), an interactive toolbox for MATLAB (The Mathworks, Inc., Natick, USA, version R2013a), was used for off-line analysis of EEG. The continuous EEG was divided into epochs from -100 ms pre- to 500 ms post-stimulus onset. EEG epochs were sorted according to stimulus type and averaged from each participant to compute the ERP. Baseline was defined as the epoch from -100 to 0 ms prior to the onset of the stimuli. The EOG channels served for off-line rejection of epochs with any eye blinks and eye movements with ocular activity larger than 50  $\mu$ V. A Custom written MATLAB script was used for further analysis. Following Senkowski et al. (2011), five mean electrode groups were calculated for the analysis, with each group comprising five electrodes: (1) 'left anterior' with electrodes AF3, F3, F5, FC3, and FCL; (2) 'right anterior' with electrodes AF4, F4, F6, FC4, and FCR; (3) 'central' with electrodes FCz, Cz, C1, C2, CPz; (4) 'left posterior' with electrodes P1, P3, PO3, O1, and PO7; and (5) 'right posterior' with electrodes P2, P4, PO4, O2, and PO8. For both age groups, group-averaged ERPs for each of the unimodal stimulus types were calculated for the identification of the auditory and visual evoked potentials.

Significant auditory and visual evoked potentials were assessed by *t*-test (two tailed), comparing the amplitude of the unimodal ERP stream against zero for each time sample between 0 and 200 ms post-stimulus. Based on Maurer et al. (2005), in this latency range the classical visual (N75, P100, N140) and auditory evoked potentials (P60, N100, P200) would be expected. Bonferroni correction for multiple comparisons was used to adjust  $\alpha = 0.01$  to  $\alpha^* = 0.001$ . As a consequence, *t*-tests would reveal significance whenever  $p < \alpha^*$ .



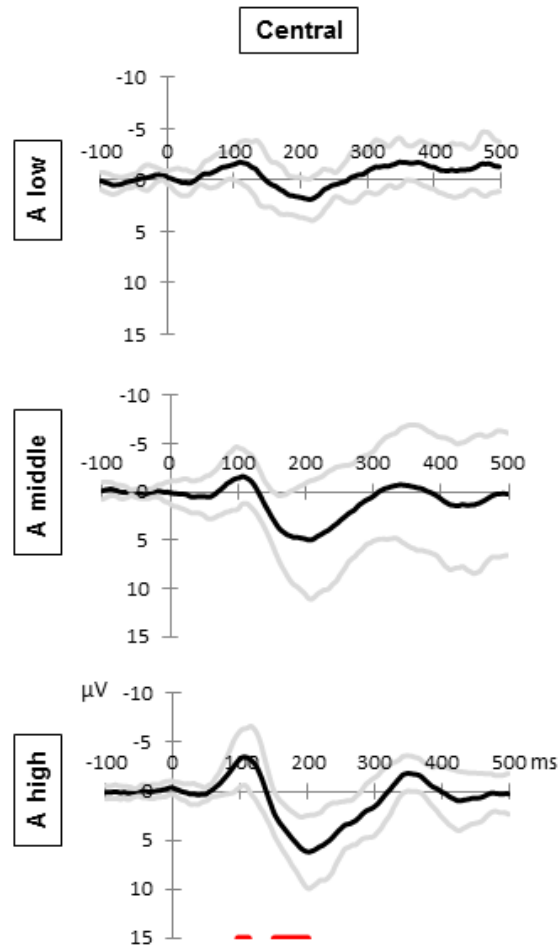
**Fig.11.** Electrode groups used for the EEG experiment based on Senkowski et al. (2011). Two anterior, two posterior, and one central group, each containing five electrodes, were analyzed, FPz served as reference. Horizontal and vertical eye movements were measured with two EOG electrodes lateral and inferior to the participant's right eye.

## 3.2. Results

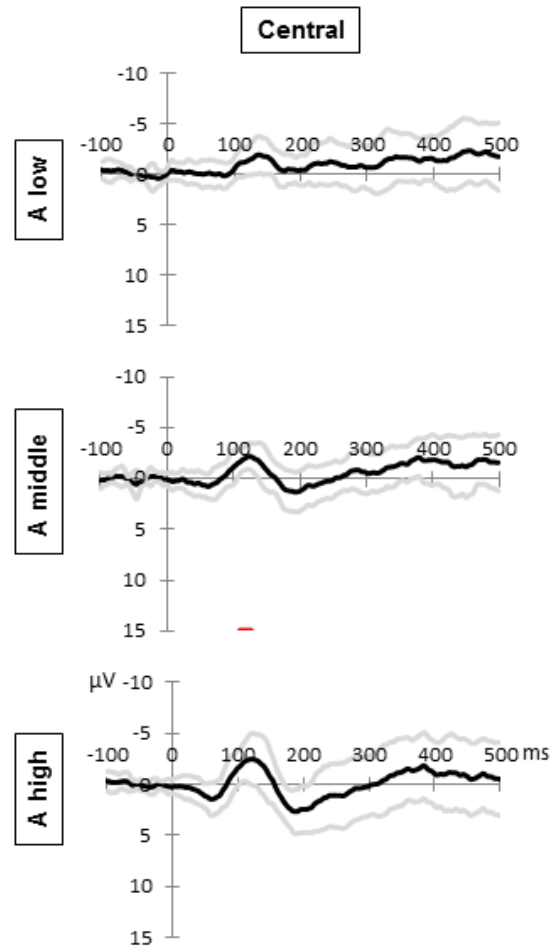
### 3.2.1. ERP waveforms

**Fig.12** and **Fig.14** show the group-averaged ERPs elicited by unimodal auditory and unimodal visual stimuli at central and two posterior electrode groups, respectively, for the young adults, while **Fig.13** and **Fig.15** illustrate the same group-averaged ERPs for the elderly adults. For both age groups, the auditory evoked potentials (AEPs) elicited by unimodal auditory stimuli (**Fig.12** and **Fig.13**) showed the expected pattern of P1 peaking at about 60 ms, N1 peaking at about 100 ms, and P2 peaking at about 200 ms (Maurer et al., 2005). The point-wise running *t*-test did not reveal significance for the latency range of all expected AEPs. Significant AEPs for young adults could be identified at high intensity in the latency range of 96-112 ms and 128-200 ms. For the elderly adults, significant AEPs could be identified at middle intensity from 110 to 126 ms. But latencies and amplitudes of the components P1, N1, and P2 could be measured in both age groups and all stimulus intensities when considering the AEPs for each individual participant.

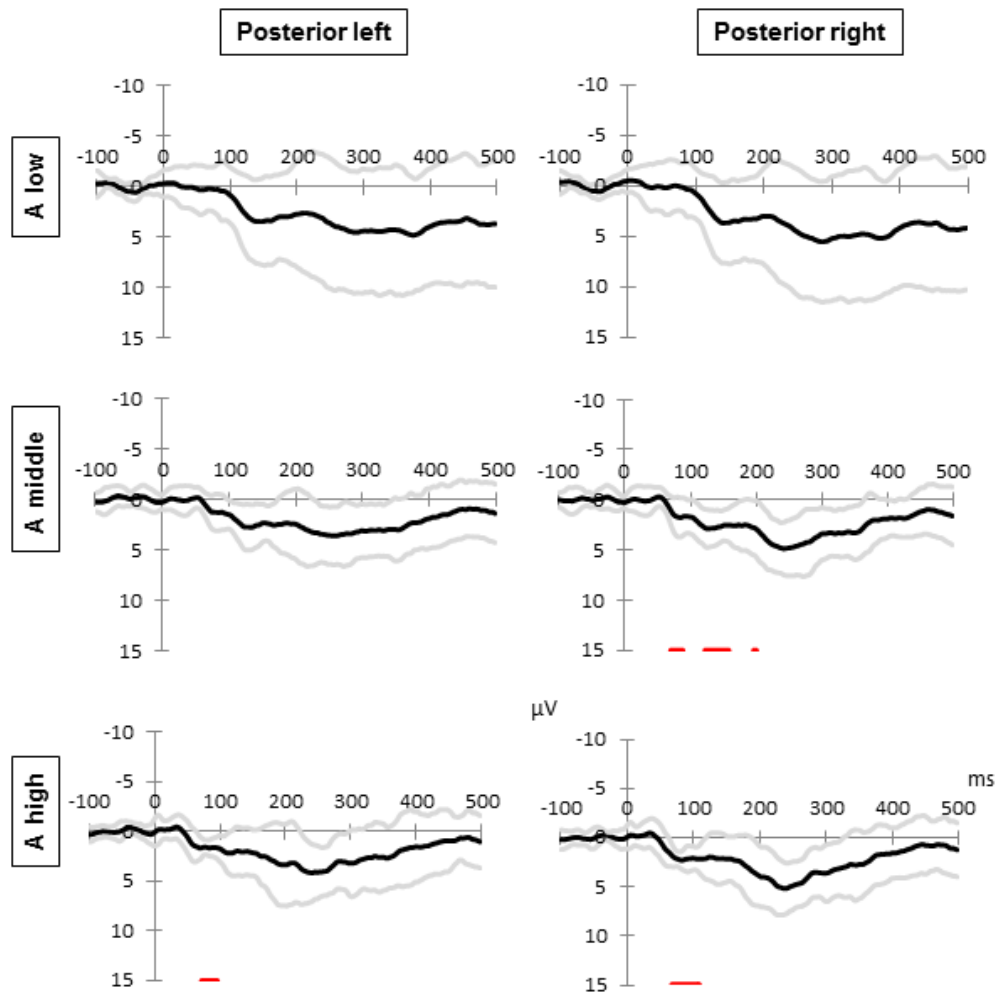
In contrast to the stable responses elicited by unimodal auditory stimuli, an irregular pattern arose for the responses elicited by unimodal visual stimuli. Group-averaged ERPs for the young age group (**Fig.14**) did not show the expected pattern of visual evoked potentials (VEPs) namely a C1 peaking at about 75 ms, a P1 peaking at about 100 ms, and a N1 peaking at about 145 ms, as described in Maurer et al. (2005). The point-wise running *t*-test revealed significant VEPs at the posterior right electrode group for the middle stimulus intensity at 40-88 ms, 122-158 ms, and 196-200 ms, and for the high intensity at 68-108 ms. Furthermore, at the left posterior electrode group for the high stimulus intensity, the VEPs differed significantly from zero in the latency range 72-96 ms. Taking a look at the individual VEPs for each young participant, it was noted that only three out of twelve participants exhibited measurable visual responses in the two posterior electrode groups. This pattern could be observed at low, middle, and high intensities. The group-averaged ERPs for the elderly adults elicited by unimodal visual stimuli (**Fig.15**) seemed to show more distinct VEPs than those for the young age group, although the point-wise running *t*-test revealed only significance in the latency range of about 75 to 90 ms at the posterior right electrode group at middle and high intensities, and at the posterior left electrode group at high intensity. However, individual VEPs for each elderly participant revealed a similar pattern than observed in the young age group. Only five out of twelve elderly participants exhibited a measurable pattern of C1, P1, and N1. These observed irregularities in VEPs in young and elderly adults raised the question of whether our VEP test with unimodal visual stimuli containing Gabor patches with vertical gratings (based on Senkowski et al., 2011) might have failed.



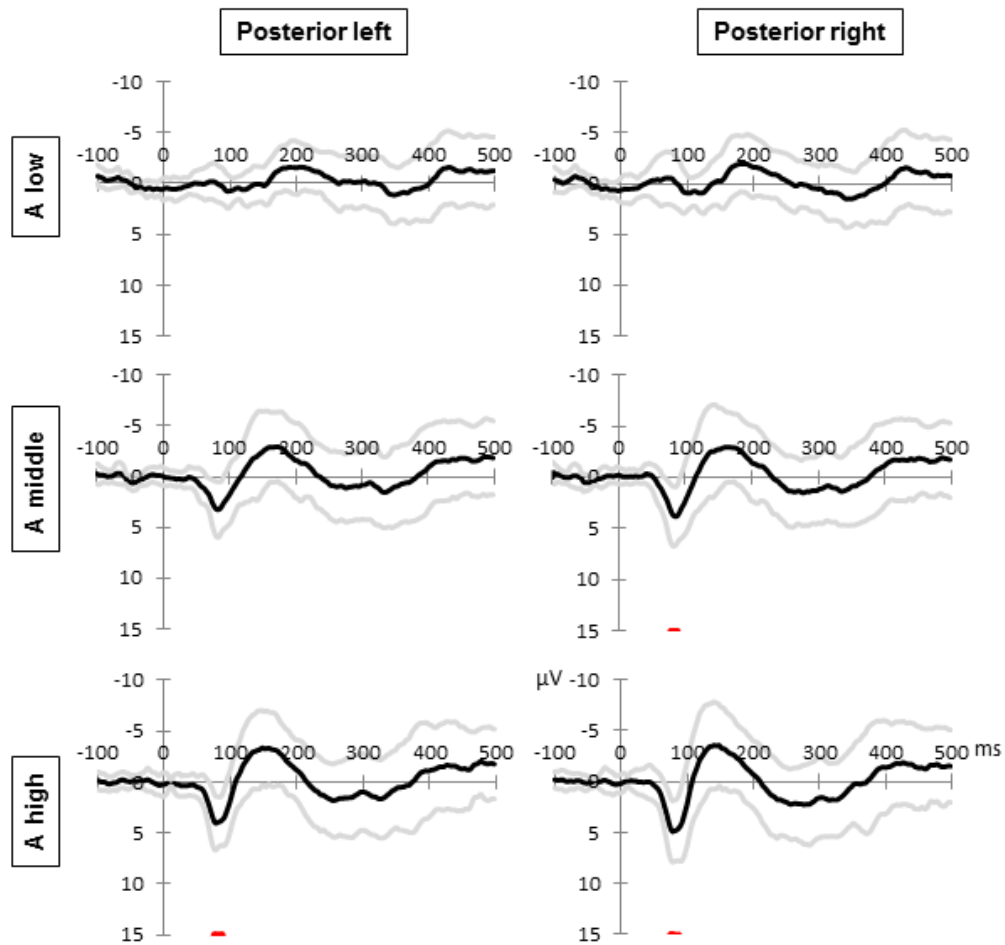
**Fig.12.** Group-averaged ERPs to unimodal auditory stimuli for the young adults. ERPs are plotted for the central electrode group as mean amplitude (black)  $\pm$  standard deviation (grey) for low, middle, and high stimulus intensity. In the bottom of each panel, red dots are available in the latency range from 0 to 200 ms when AEPs differ significantly from zero.



**Fig.13.** Group-averaged ERPs to unimodal auditory stimuli for the elderly adults. ERPs are plotted for the central electrode group as mean amplitude (black)  $\pm$  standard deviation (grey) for low, middle, and high stimulus intensity. In the bottom of each panel, red dots are available in the latency range from 0 to 200 ms when AEPs differ significantly from zero.



**Fig.14.** Group-averaged ERPs to unimodal visual stimuli for the young adults. ERPs are plotted for the posterior left and right electrode groups as mean amplitude (black)  $\pm$  standard deviation (grey) for low, middle, and high stimulus intensity. In the bottom of each panel, red dots are available in the latency range from 0 to 200 ms when VEPs differ significantly from zero.



**Fig.15.** Group-averaged ERPs to unimodal visual stimuli for the elderly adults. ERPs are plotted for the posterior left and right electrode groups as mean amplitude (black)  $\pm$  standard deviation (grey) for low, middle, and high stimulus intensity. In the bottom of each panel, red dots are available in the latency range from 0 to 200 ms when VEPs differ significantly from zero.

### 3.3. Discussion

The initial thought regarding the present study was to replicate the study by Senkowski et al. (2011), which investigated multisensory integration in young participants with unimodal visual, unimodal auditory, and bimodal audiovisual stimuli at low, middle, and high intensities. This study was to be extended to the point that a young and an elderly age group were tested to compare the multisensory integration mechanisms available in the different age groups. Thus, we used the same visual (Gabor patch) and auditory (1000 Hz pure tone) stimuli as Senkowski et al. (2011) and (slightly) decreased only the intensity levels of the auditory stimulus.

Our results showed stable individual AEPs for each participant, which is in line with Senkowski and colleagues (2011), who reported on an auditory P1 peaking at about 60 ms and an auditory N1 peaking at about 100 ms. However, only an irregular pattern of individual VEPs for each participant could be observed in the current study, which is inconsistent with Senkowski et al. (2011) showing VEPs like C1 (~70 ms) and P1 (~100 ms). The absence of a clear VEP pattern in our study leads to the belief that the used Gabor patches were not sufficient enough (e.g. in form) to elicit the expected VEPs. In our study, only three young and five elderly participants out of 24 participants in total showed measurable VEPs like C1, P1, and N1. Thus, three to four times as many participants would have to be tested in order to receive applicable data for twelve participants in each age group. But also in this case the validity would be reduced as the recorded data would only represent one third or fourth of the population.

The observable deficiencies in measuring VEPs raised the question of whether EEG electrodes used in this study are damaged. Indeed, this could not be the case, because the following EEG experiment (see **Chapter 4**) using the same electrodes will show that AEPs and VEPs could be measured with a good quality. Furthermore, it may be suggested that the posterior left and right electrode groups were not the best positions to record VEPs. Nevertheless, these groups contained electrodes which were well-placed above the visual cortex where VEPs such as C1, P1, and N1 are predominantly generated (Cobb & Dawson, 1960; Mangun, 1995).

As a consequence of the irregularities in the VEPs with Gabor patches as visual stimuli, we decided to change the visual stimulus. In the subsequent study, visual stimuli will be consisted of full screen checkerboards instead of Gabor patches.

In addition to changes in the visual stimulus, several other parameters were modified for the subsequent study. The changes and modifications include the following points:



- The number of stimulus intensities will be reduced to only two intensities. Low and middle intensities of the present study will be used for the subsequent study, but named as 'low' and 'high', respectively.
- SOAs will be introduced to investigate whether it has an influence on audiovisual integration measured with EEG. Thus, bimodal stimuli will be presented with a shift in the onset of the corresponding unimodal stimuli, resulting in three different SOAs: -50 (A precedes V), 0, and +50 ms (V precedes A).
- The task paradigm will be changed to a perceptual task on visual target stimuli ignoring any auditory non-targets (FAP), but with no demand for a manual response.
- The number of electrodes will be reduced to twelve active scalp electrodes, placed at central, temporal, posterior, and occipital sites.

For details and results of the subsequent EEG experiment see **Chapter 4**.

## 4. Experiment 3: EEG experiment

The third study assessed the age-related changes in multisensory integration mechanisms with an electrophysiological approach. It was designed to solve the problems of Experiment 2 in the measurement of visual evoked potentials with the help of a different unimodal visual stimulus (checkerboard) as compared to that used in Experiment 2 (Gabor patch). Further, the influence of SOA on the audiovisual integration mechanisms should be investigated. As became obvious in Experiment 1 (see **Chapter 2**), SOA can have a significant influence on the length of the RT. If the bimodal stimulus is presented with an adequate SOA, it could even cause shortening of the RT as compared to a bimodal stimulus, which consisted of no SOA.

Hence, the purpose of the present experiment was to examine the age-related changes in audiovisual integration performance and to assess the influence of stimulus intensity and SOA on audiovisual integration. On the basis of previous studies (e.g., Fort et al., 2002b, 2002a; Giard & Peronnet, 1999; Molholm et al., 2002) reporting on audiovisual integration effects in the latency range of 100 to 200 ms, the focus of the present experiment was also on this range. Moreover, because of the fact that the latency range 40 to 90 ms has also been mentioned in several previous studies (e.g., Giard & Peronnet, 1999; Molholm et al., 2002), we decided to investigate the audiovisual integration in young and elderly adults in this latency range as well. Based on the theoretical background, two hypotheses could be generated.

**Hypothesis 6** is based on several EEG studies, which reported that multisensory interaction in young adults occurs in the time range of 100-200 ms poststimulus (Fort et al., 2002b, 2002a; Gao et al., 2014; Giard & Peronnet, 1999; Gondan & Röder, 2006; Molholm et al., 2002). Furthermore, SRT and RT experiments showed that elderly adults exhibit slower SRTs (Diederich et al., 2008) and RTs (Laurienti et al., 2006; Stephen et al., 2010) than young adults. Based on the aforementioned studies, Hypothesis 6 claims that multisensory interaction (MI) occurs within 100 and 200 ms poststimulus ( $t_{100-200}$ ) and differs between young and elderly adults:

$$MI(t_{100-200})_{\text{young}} \neq MI(t_{100-200})_{\text{old}}.$$

**Hypothesis 7** is based on Giard and Peronnet (1999) and Molholm et al. (2002), who exhibited multisensory interaction in the time range of 40-90 ms poststimulus. Due to studies by Diederich et al. (2008), Laurienti et al. (2006), and Stephen et al. (2010), which reported slower SRTs and RTs for elderly than young adults, Hypothesis 7 suggests that young and elderly adults differ in their early audiovisual interaction (MI) in the time range of 40-90 ms poststimulus ( $t_{40-90}$ ):

$$MI(t40-90)_{\text{young}} \neq MI(t40-90)_{\text{old}}.$$

## 4.1. Materials and methods

### 4.1.1. Participants

Twenty-four, young and elderly paid adults participated in the present study. One participant of each age group was excluded due to a noisy EEG signal. The remaining eleven young (aged 18-28 years,  $M = 22.91$ ,  $SD = 3.39$ , six female) and eleven elderly adults (aged 66-73 years,  $M = 69.75$ ,  $SD = 1.86$ , ten female), who were different from the participants in Experiment 1 and 2, reported normal hearing and had normal or corrected-to-normal vision. Young adults were students at the University of Bremen, whereas the elderly adults were recruited from a pool of participants, who had registered for a former experiment at the Jacobs University Bremen. Participants provided a written informed consent and agreed with the anonymous storage, analysis, and publication of the data. For an expense allowance participants received 9 € per hour and a single flat rate for travel expense of 5 €. The experiment was conducted according to the principles expressed in the Declaration of Helsinki (1964).

### 4.1.2. Procedure and stimulus conditions

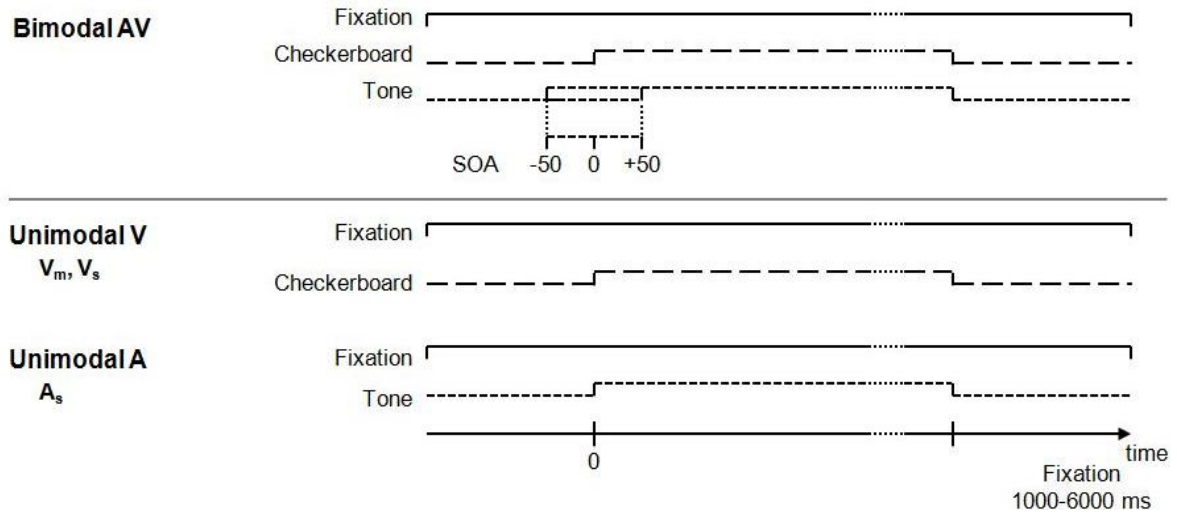
The experiment was conducted in a darkened but not electrostatically shielded room at the Jacobs University Bremen. Participants were seated 57 cm apart from a monitor and were instructed to fixate a fixation point (a white or red cross), which was visible at the center of the monitor during the whole experiment.

Participants received a randomized stream of unimodal auditory (A), unimodal visual (V), and bimodal audiovisual (AV) stimuli. All stimulus types were presented at both low and high intensities. During the experiment, participants were instructed to fixate the fixation point with no demand for a manual response. Their eye movements were controlled via electrooculogram (EOG).

**Fig.16** illustrates the time course of the single unimodal and bimodal trials. The visual stimuli consisted of checkerboards, which were recommended as standard patterned stimuli for eliciting VEPs (Odom et al., 2004). Checkerboards were presented over the whole 19" computer monitor (size of the squares: 2 x 2 cm). Stimuli had a mean luminance constant at a level of 20 cd/m<sup>2</sup>. Michelson contrast ( $((\text{maximal luminance} - \text{minimal luminance}) / (\text{maximal luminance} + \text{minimal luminance})) * 100 \%$ ) of low and high intensities was 10 % and 50 %, respectively.

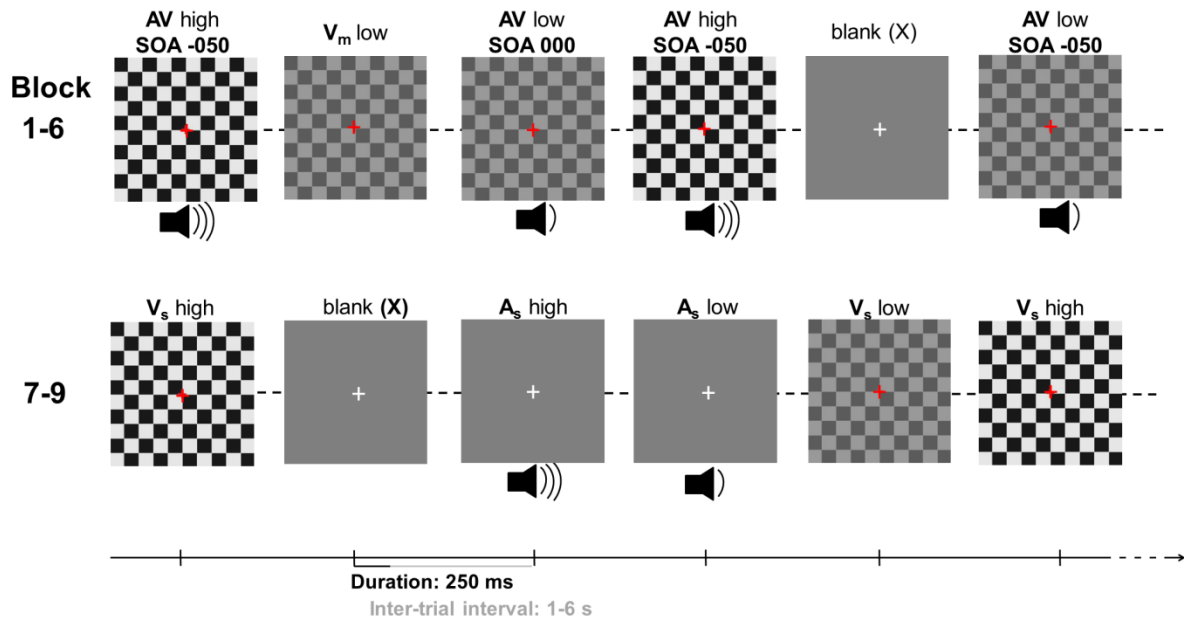
respectively. Auditory stimuli consisted of pure tones with a frequency of 1000 Hz, which were presented via two external stereo speakers placed to the left and to the right of the monitor. Auditory stimuli comprised of low and high intensities with sound-pressure levels of 40 and 65 dB, respectively. Bimodal audiovisual stimuli consisted of corresponding combined unimodal stimuli of the same intensity level (low A + low V = low AV and high A + high V = high AV). The auditory stimuli were presented with an SOA of +50, 0 or -50 ms, with negative value meaning that the non-target (A) was presented before the target (V), whereas a positive value indicates that the non-target was presented after the onset of the target. With a rate of 20 %, non-stimulus events (blanks, X) were intermixed into the stream of uni- and bimodal stimuli.

During the experiment, one part of the unimodal visual stimuli was intermixed with the stream of bimodal audiovisual stimuli; the second part of the unimodal visual stimuli was presented separately from bimodal stimuli. The same labelling of the unimodal auditory and visual stimuli as established for the RT experiment (see 2.1.2) also applies for the EEG experiment: Intermixed unimodal visual stimuli are labelled as 'mixed unimodal visual stimuli' ( $V_m$ ), whereas separately presented unimodal visual stimuli are labelled as 'separated unimodal visual stimuli' ( $V_s$ ). Unimodal auditory stimuli were always presented separately from bimodal stimuli, whereby these were labelled as 'separated unimodal auditory stimuli' ( $A_s$ ). All unimodal ( $V_m$ ,  $V_s$ ,  $A_s$ ) and bimodal (AV) stimuli were presented for 250 ms (for auditory stimuli ( $A_s$ , AV): 10 ms rise and fall times). The entire session was divided into nine blocks of about 5 minutes (200 trials in each block) of duration each. In blocks 1-6 only bimodal and mixed unimodal visual  $V_m$  stimuli were presented, whereas in blocks 7-9 only separated unimodal auditory  $A_s$  and unimodal visual  $V_s$  stimuli were presented. The twelve stimulus types ( $A_s$  low,  $A_s$  high,  $V_s$  low,  $V_s$  high,  $V_m$  low,  $V_m$  high,  $AV_{+50}$  low,  $AV_0$  low,  $AV_{-50}$  low,  $AV_{+50}$  high,  $AV_0$  high,  $AV_{-50}$  high) were offered in random order with equal frequencies of 120 trials. Blanks (X) were intermixed with a frequency of 360 trials. The inter-trial interval varied randomly (truncated exponential) between 1 and 6 s.

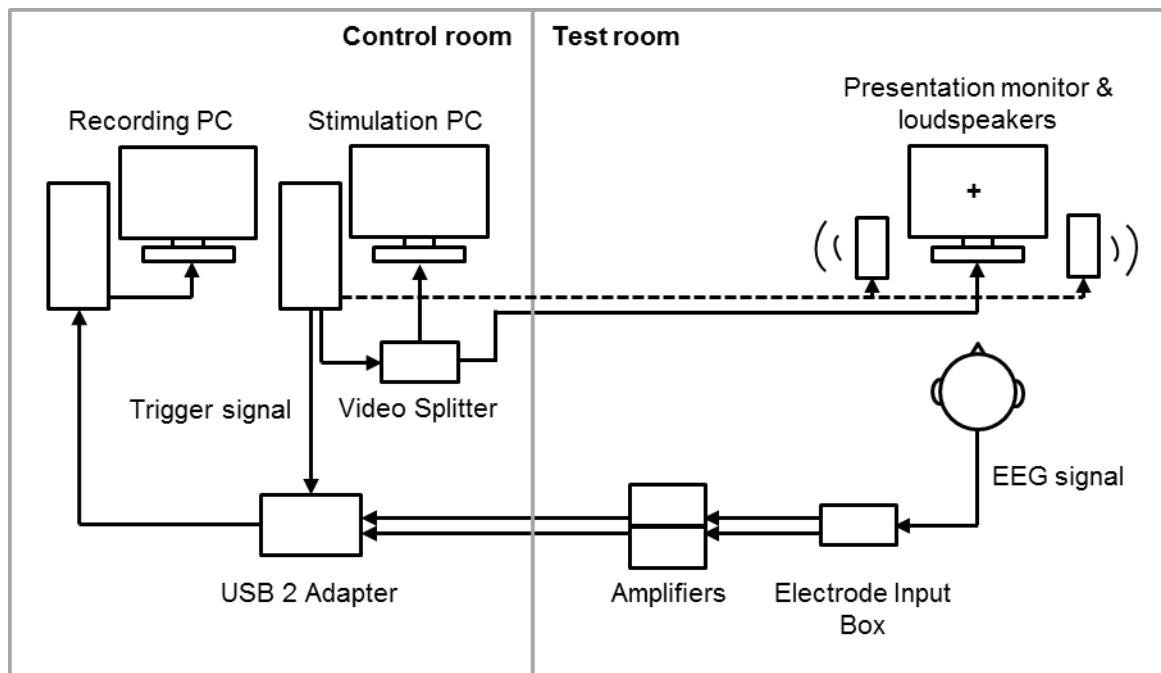


**Fig.16.** Time course of a single trial. The fixation was visible during the whole experiment. *Top:* Time course for a bimodal audiovisual stimulus. The auditory stimulus (dotted) started 50 ms before or 50 ms after or with the same onset of the visual stimulus (dashed). *Bottom:* Time course for unimodal visual ( $V_m$  and  $V_s$ ) and unimodal auditory ( $A_s$ ) stimuli.

**Fig.17** illustrates an exemplary experimental setup and **Fig.18** displays an exemplary schematic setup of the laboratory. Stimuli were presented by a stimulation PC with Linux operating system (Ubuntu 14.04 LTS). The monitor was driven through a AMD Radeon HD 7470 OEM video card. A Video Splitter (Aten International Co., Ltd., New Taipei City, Taiwan) divided the video signal of the stimulation PC in order to receive the same signal on both the control and the presentation monitor. A custom-written C program (Dennis Ritchie & Bell Labs, Murray Hill, NJ, USA) using the OpenGL (Khronos Group Inc., Beaverton, OR, USA) and the OpenAL (Creative Technology Ltd., Singapore) libraries controlled the stimulus presentation. The exact timing between visual and acoustical stimulation was adjusted to the millisecond level using an oscilloscope equipped with custom-built photo LEDs and a microphone. The EEG signal was passed through an Electrode Input Box (Brain Products GmbH, Gilching, Germany) and two amplifiers to an USB 2 adapter (Brain Products GmbH, Gilching, Germany). Together with the trigger and the pattern signal, submitted by the stimulation PC, the EEG signal was transmitted to the EEG recording PC with Windows operating system (Windows 7). BrainVision Recorder (Brain Products, Gilching GmbH, Germany) was used for recording the EEG and saving it for later off-line analysis.



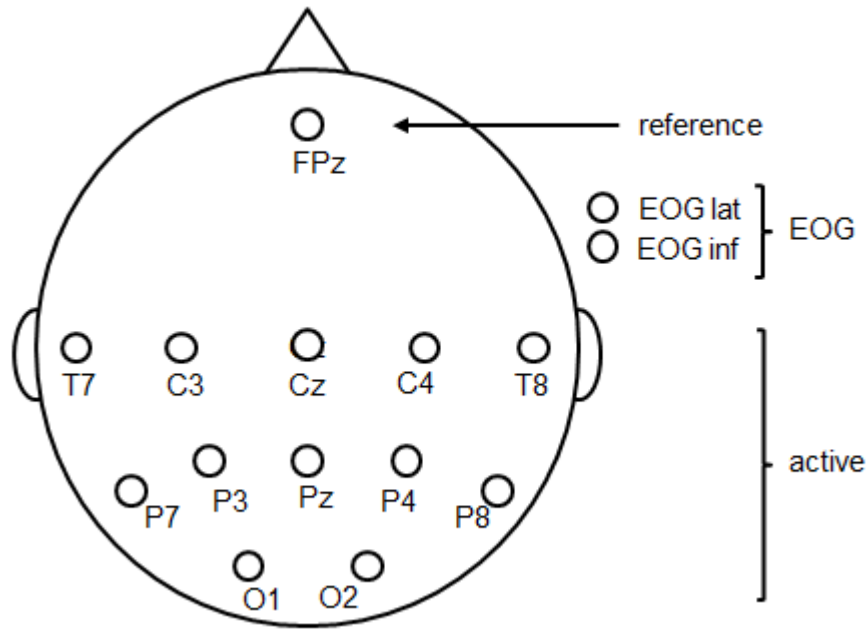
**Fig.17.** Exemplary experimental setup. Participants were presented with a randomized stream of unimodal auditory (A), unimodal visual (V), and bimodal audiovisual (AV) stimuli of low and high intensity with varying stimulus onset asynchronies (SOAs) for the bimodal stimuli. During the blocks 1-6 bimodal audiovisual stimuli were intermixed with unimodal visual stimuli ( $V_m$ ), whereas during the blocks 7-9 only separated unimodal visual ( $V_s$ ) and auditory stimuli ( $A_s$ ) were presented. Blanks were intermixed during all blocks. Participants were instructed to fixate the fixation point with no demand for any manual response.



**Fig.18.** Exemplary schematic setup of the laboratory. The stimulus presentation and EEG recording took place in the control room (left), whereas the participant sat in the test room (right). Presentation monitor and loudspeakers in the test room were controlled through the stimulation PC. During the experiment, participants sat in front of the monitor and fixated a fixation cross. Continuous EEG was acquired from 12 active scalp electrodes, which were connected to an Electrode Input Box and forwarded through two amplifiers to an USB 2 adapter. Together with the trigger and pattern signal from the stimulation PC, the EEG signal was transferred to the recording PC.

### 4.1.3. EEG data acquisition and analysis of event-related potentials

Continuous EEG was acquired from 12 active scalp electrodes (Ag/AgCl sintered ring electrodes), which were mounted into an elastic cap (EASYCAP GmbH, Herrsching, Germany), versus a reference electrode at FPz. Scalp electrodes were placed at FPz, Cz, C3, C4, T7, T8, Pz, P3, P4, P7, P8, O1, and O2, according to the International 10-20 System (see **Fig.19**). Abralyt 2000 (EASYCAP GmbH, Herrsching) was used as a chloride-free, abrasive electrolyte gel during the recordings. The sampling rate was 500 Hz; the band-pass filter was set from 0.1 to 166 Hz. In addition, a 50 Hz low-pass filter was used. Horizontal and vertical eye movements were measured with two electrooculogram (EOG) electrodes placed lateral and inferior to the participant's right eye, respectively. EEGLAB (Swartz Center for Computational Neuroscience, San Diego, USA, version v12.0.2.3b), an interactive toolbox for MATLAB (The Mathworks, Inc., Natick, USA, version R2013a), was used for off-line analysis of EEG. The continuous EEG was divided into epochs from -66 ms pre- to 532 ms poststimulus. EEG epochs were sorted according to stimulus type and averaged from each participant to compute the ERP. Baseline was defined as the epoch from -66 to 0 ms prior to the onset of the stimuli. The EOG channels served for off-line rejection of epochs with any eye blinks and eye movements with ocular activity larger than 50  $\mu$ V. A Custom written MATLAB script was used for further analysis. Four mean electrode groups were calculated for the analysis: (1) O1/O2 as mean of the electrodes O1 and O2; (2) P3/P4 as mean of P3 and P4; (3) P7/P8 as mean of P7 and P8; and (4) T7/T8 as mean of T7 and T8. For both age groups, group-averaged ERPs for each of the stimulus types were calculated for the identification of the auditory P1, N1, and P2, and visual N1, P1, and N2.



**Fig.19.** Electrode positions used for the EEG recording. Continuous EEG was acquired from 12 active scalp electrodes, FPz served as reference. Horizontal and vertical eye movements were measured with two EOG electrodes lateral and inferior to the participant's right eye.

The difference wave  $AV-(A+V)+X$  computed by subtracting the sum of the responses to the unimodal auditory and visual stimuli from the response to the bimodal audiovisual stimulus (Barth et al., 1995) and by adding the response to a non-stimulus event (blank, X), was used to investigate auditory-visual interaction. The reason for this calculation is that ERPs to a bimodal (AV) stimulus are equal to the sum of the corresponding unimodal responses (A+V), plus the reputed neural activities related to the bimodal nature of the stimuli (auditory-visual interaction) (Besle et al., 2004). The ERP to the non-stimulus (X) is added to eliminate any common activity related to target processing (e.g. P300), motor processing or selection of a response. Six difference waves were calculated (+50 ms low, 0 ms low, -50 ms low, +50 ms high, 0 ms high, -50 ms high) for each of the SOAs, +50, 0, and -50 ms and for each stimulus intensity. This difference wave was computed using only the separated unimodal auditory and visual stimuli ( $V_s$  and  $A_s$ ).

Based on previous reports on multisensory interaction between 110 and 200 ms (Fort et al., 2002b; Gao et al., 2014; Giard & Peronnet, 1999; Molholm et al., 2002; Teder-Sälejärvi et al., 2002), the focus of the statistical analysis of the multisensory interactions in the present study was on the time interval between 100 and 200 ms. Thus, to investigate Hypothesis 6, stating that multisensory interaction occurs within 100 and 200 ms poststimulus and differs between young and elderly adults, first the latency and the amplitude of the most positive peak within the predefined time range was measured for each participant in each of the six difference waves and for each stimulus intensity. Latencies and amplitudes were then



submitted to two separate repeated-measure ANOVAs (latency, amplitude) to determine whether SOA or stimulus intensity had a general influence on the latency or the amplitude of the multisensory integration potential between the two age groups. The within-subject factors 'SOA' (+50, 0, -50 ms) and 'Stimulus Intensity' (low, high), and the between-subject factor 'Age' (young, old) were used.

Because former studies (Cappe et al., 2010; Giard & Peronnet, 1999; Molholm et al., 2002; Senkowski et al., 2011) also reported early multisensory interactions between 40 and 90 ms, this time range was also tested for possible effects of audiovisual interaction (Hypothesis 7). To this end, the time range between 40 and 90 ms was divided into five time bins of 10 ms of duration each and activation therein averaged. A repeated-measures ANOVA was performed to investigate if early interactions between the two age groups are influenced by the SOA, the stimulus intensity or the time bin. For this ANOVA, the within-subject factors 'SOA' (+50, 0, -50 ms), 'Stimulus Intensity' (low, high), and 'Time Bin' (40-50, 50-60, 60-70, 70-80, 80-90 ms), and the between-subject factor 'Age' (young, old) were used.

Finally, a post-hoc analysis was performed on the negative potential occurring around 215 ms and the positive potential occurring around 255 ms. For this post-hoc analysis two repeated-measure ANOVAs were conducted, using the within-subject factors 'SOA' (+50, 0, -50 ms), and 'Stimulus Intensity' (low, high), and the between-subject factor 'Age' (young, old).

Greenhouse-Geisser corrections were used in reporting the  $p$  values when appropriate. An  $\alpha = 0.05$  was used for all statistical tests.

## 4.2. Results

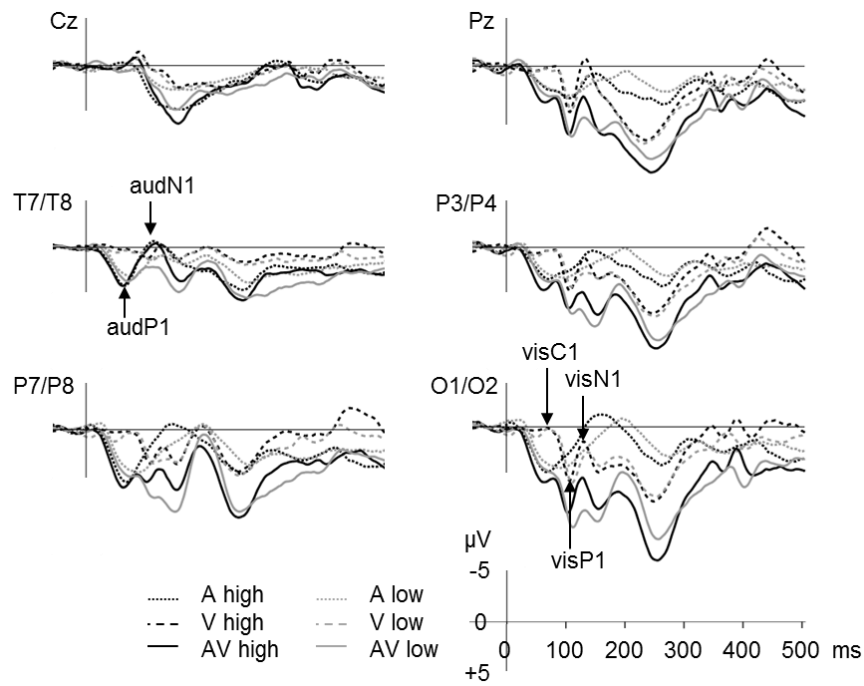
### 4.2.1. ERP waveforms

**Tab.4** shows the mean latencies and amplitudes of the main components elicited by unimodal visual and auditory stimuli at low and high intensities for both age groups. The ERP elicited by the unimodal visual stimulus type was characterized by three typical visual components at the electrode group O1/O2: C1 peaking at about 75 ms, P1 peaking at about 110 ms, and N1 peaking at about 150 ms. The ERP elicited by the unimodal auditory stimulus type was characterized by typical auditory components at electrode group T7/T8: P1 peaking at about 70 ms, N1 peaking at about 120 ms, and P2 peaking at about 200 ms.

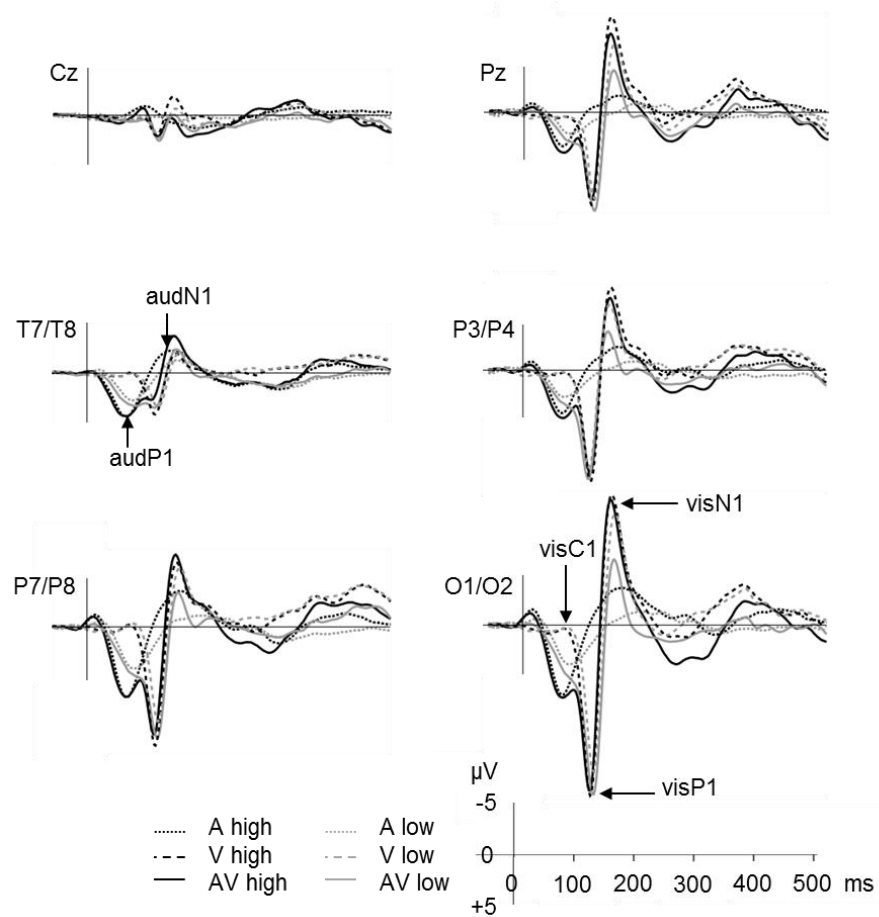
Bimodal audiovisual stimuli with an SOA of 0 ms elicited both auditory and visual ERP waveforms, which showed similarities to those elicited by unimodal stimuli. **Fig.20** and **Fig.21** present the group-averaged ERPs for young and elderly adults, respectively. They show unimodal auditory, unimodal visual, and bimodal audiovisual stimuli of low and high intensity over a time period of -50 to 500 ms over a subset of electrode sites.

**Tab.4.** Amplitudes and latencies of the visual (VEP at electrode group O1/O2) and auditory (AEP at electrode group T7/T8) evoked potentials. Amplitudes (in  $\mu\text{V}$ ) and latencies (in ms) are shown as means  $\pm$  standard errors ( $n(\text{young}) = 11$ ;  $n(\text{old}) = 11$ ).

VEP			C1	P1	N1
High	young	ms	73.09 ± 4.28	113.64 ± 5.97	144.91 ± 9.56
		µV	-0.77 ± 0.61	8.54 ± 1.96	-1.06 ± 1.82
	old	ms	68.55 ± 1.75	113.09 ± 1.33	150.73 ± 3.33
		µV	0.18 ± 0.41	19.15 ± 2.40	-15.14 ± 2.48
Low	young	ms	76.36 ± 2.90	118.55 ± 5.93	150.73 ± 7.93
		µV	-0.44 ± 0.78	8.08 ± 2.05	0.46 ± 2.03
	old	ms	74.18 ± 3.10	118.18 ± 1.39	156.73 ± 3.88
		µV	-0.15 ± 0.56	16.77 ± 2.18	-13.23 ± 2.17
AEP			P1	N1	P2
High	young	ms	64.73 ± 1.81	119.45 ± 5.84	190.73 ± 7.03
		µV	4.35 ± 0.55	-1.39 ± 0.66	3.41 ± 0.78
	old	ms	66.55 ± 2.55	139.45 ± 4.57	211.64 ± 4.41
		µV	5.07 ± 0.62	-2.66 ± 0.61	1.06 ± 0.58
Low	young	ms	72.73 ± 3.12	119.27 ± 4.00	194.00 ± 11.34
		µV	3.42 ± 0.50	0.65 ± 0.51	2.90 ± 0.65
	old	ms	76.00 ± 2.50	138.55 ± 6.91	214.73 ± 5.23
		µV	3.07 ± 0.42	-1.58 ± 0.39	0.53 ± 0.51



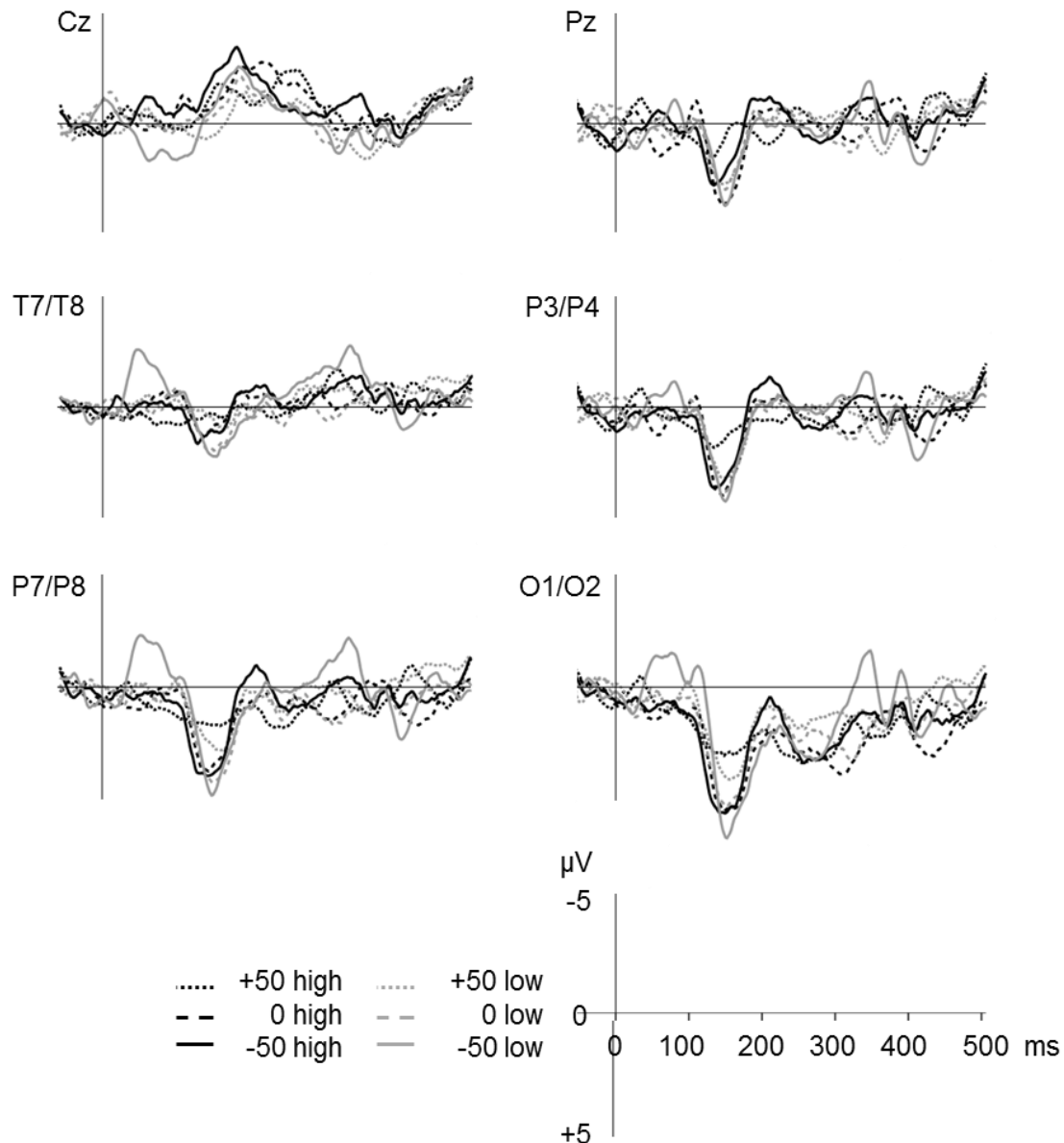
**Fig.20.** Group-average ERPs across eleven young subjects evoked by auditory (A), visual (V), and audiovisual (AV, SOA of 0 ms) stimuli of low and high intensities at the electrodes Cz and Pz, and the mean electrode groups T7/T8, P3/P4, P7/P8, and O1/O2 from -50 ms before the stimulus to 500 ms after.



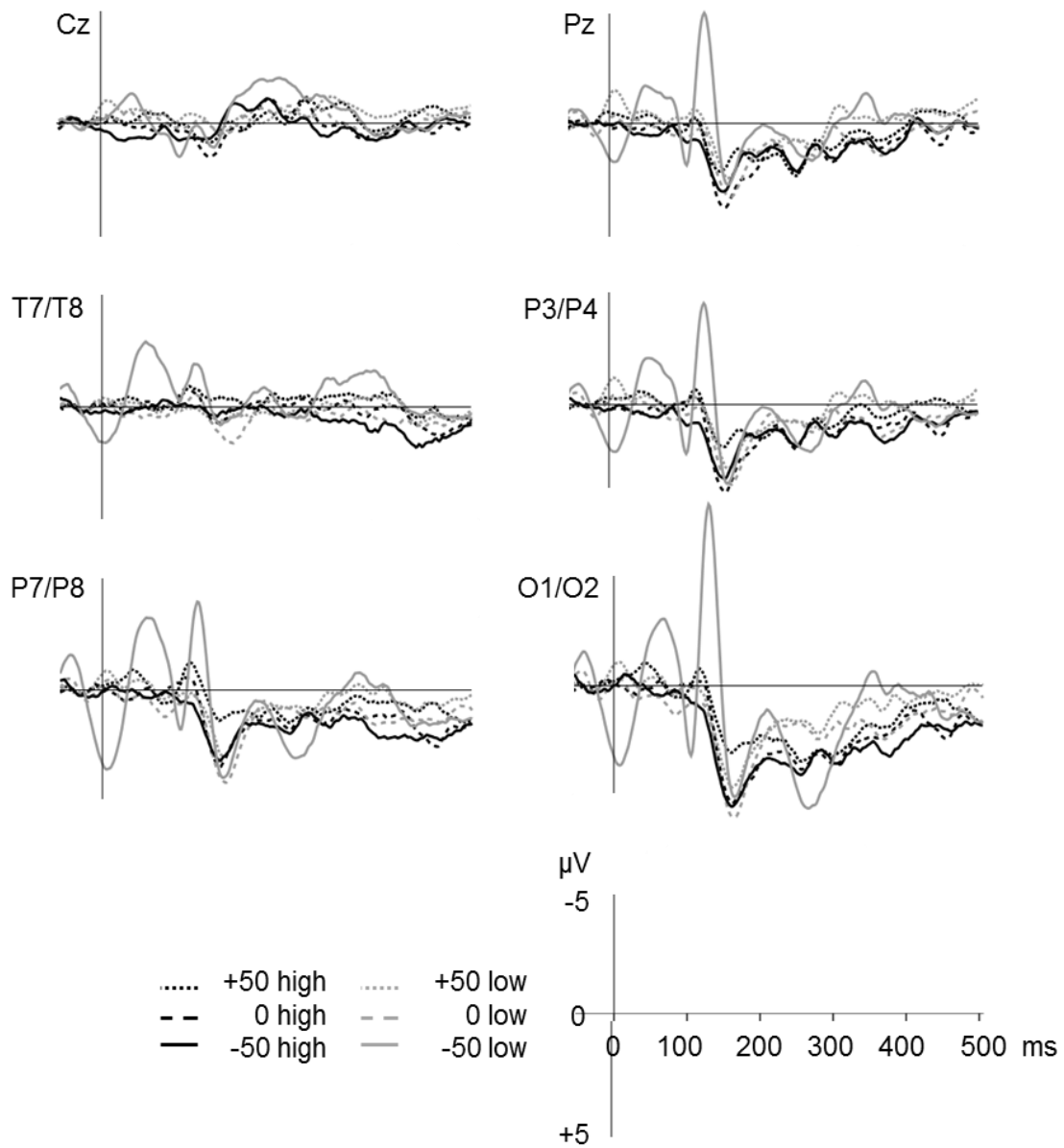
**Fig.21.** Group-average ERPs across eleven elderly subjects evoked by auditory (A), visual (V), and audiovisual (AV, SOA of 0 ms) stimuli of low and high intensities at the electrodes Cz and Pz, and the mean electrode groups T7/T8, P3/P4, P7/P8, and O1/O2 from -50 ms before the stimulus to 500 ms after.

#### 4.2.2. Audiovisual interactions

Interactions between two different modalities were assessed in the differences  $AV-(A+V)+X$  between the responses to the bimodal (AV) stimulus and the sum of the two unimodal auditory and visual responses (A+V). The ERP to the non-stimulus (X) was added to eliminate any common activity. **Fig.22** and **Fig.23** show the group-average differences for the young (**Fig.22**) and elderly (**Fig.23**) age group at low and high intensities and for the SOA of +50, 0, and -50 ms. For both age groups, difference waves show a distinct peak within the focused time range of 100 to 200 ms, indicating audiovisual interaction.

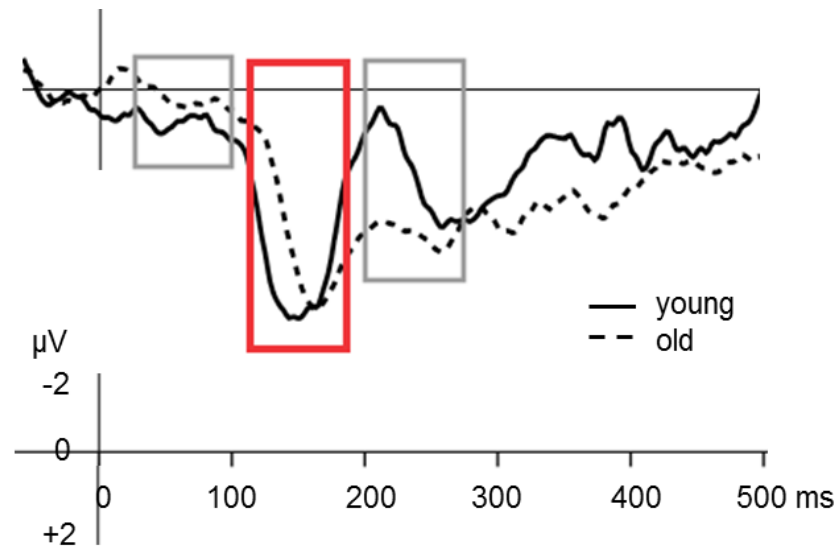


**Fig.22.** Group-average ERPs to the difference  $AV-(A+V)+X$  between the bimodal audiovisual and the sum of the two unimodal auditory and visual stimuli (plus ERP to the non-stimulus event) across eleven young subjects at the electrodes Cz and Pz, and the mean electrode groups T7/T8, P3/P4, P7/P8, and O1/O2 from -50 ms before the stimulus to 500 ms after. For each SOA (+50, 0, and -50 ms) and each stimulus intensity a difference wave was computed.



**Fig.23.** Group-average ERPs to the difference  $AV-(A+V)+X$  between the bimodal audiovisual and the sum of the two unimodal auditory and visual stimuli (plus ERP to the non-stimulus event) across eleven elderly subjects at the electrodes Cz and Pz, and the mean electrode groups T7/T8, P3/P4, P7/P8, and O1/O2 from -50 ms before the stimulus to 500 ms after. For each SOA (+50, 0, and -50 ms) and each stimulus intensity a difference wave was computed.

Hereafter, three periods (see **Fig.24**) of audiovisual interactions were described point by point: (1) audiovisual interactions from 100 to 200 ms, (2) early audiovisual interactions from 40 to 90 ms, and (3) later audiovisual interactions at 215 and 255 ms.



**Fig.24.** Overview over the three time periods, which were investigated in the analysis. Group-average ERPs to the difference AV-(A+V)+X for young (solid line) and elderly adults (dashed line) by the example at an SOA of -50 ms and high stimulus intensity. The central period around the positive peak at about 150 ms is shown in red, whereas the early (40-90 ms) and later (215 and 255 ms) periods are shown in grey.

### Audiovisual interactions from 100 to 200 ms

**Tab.5** and **Tab.6** display the means and standard deviations of the latencies (**Tab.5**) and amplitudes (**Tab.6**) of the positive peak between 100 and 200 ms (hereafter labelled as P150) for both age groups. The amplitude of the observed component decreased from the electrode group O1/O2 to the electrode groups P3/P4, P7/P8, and Pz to the electrode groups T7/T8 and Cz. This decline in the amplitude could be observed for each of the SOAs, stimulus intensities, and age groups. Exemplary this trend is shown by the example of an SOA of -50 ms at high intensity (see **Fig.25**). Due to the fact that the amplitude of the P150 is most prominent at occipital sites, the further analysis of audiovisual interaction in all three time periods is conducted only for the electrode group O1/O2.

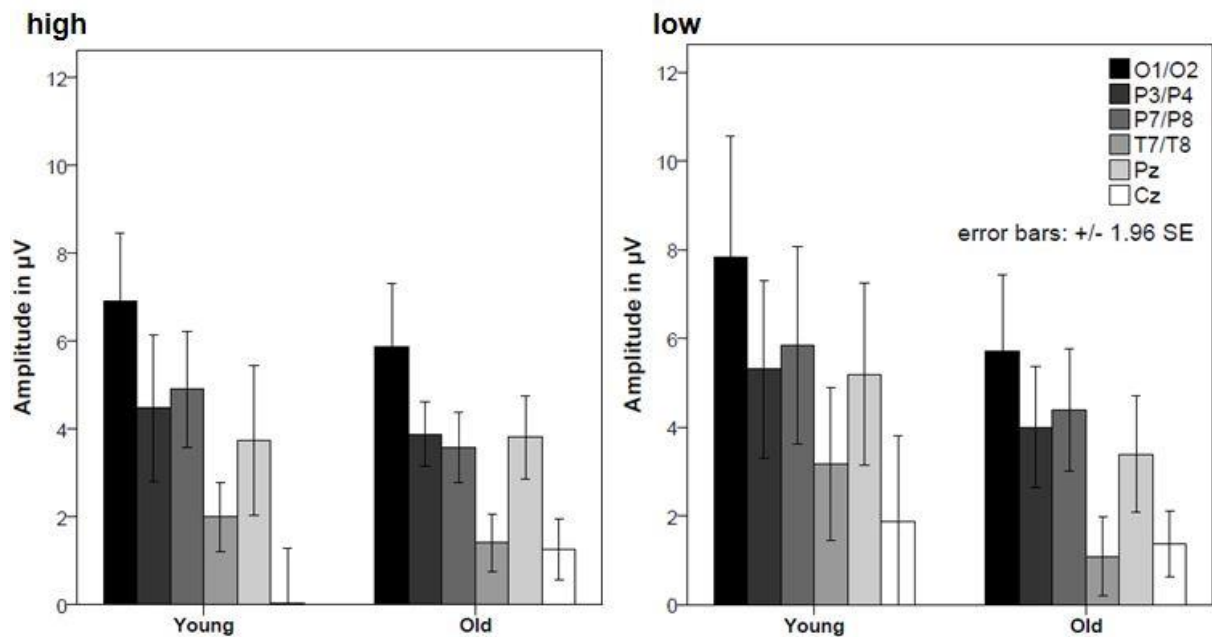
**Tab.5.** Latencies of the P150 in the difference wave AV (A+V)+X for each age group, SOA, and stimulus intensity. The latencies (in ms) are shown as means  $\pm$  standard errors (for young and old:  $n = 11$ ).

Electrode	Intensity	Age	SOA		
			-50	0	+50
Pz	high	young	144.91 $\pm$ 4.85	144.18 $\pm$ 2.90	134.73 $\pm$ 6.51
		old	153.45 $\pm$ 4.20	156.36 $\pm$ 2.48	150.00 $\pm$ 3.93
	low	young	146.91 $\pm$ 6.20	149.27 $\pm$ 3.58	151.27 $\pm$ 6.41
		old	164.18 $\pm$ 4.04	160.55 $\pm$ 3.67	166.36 $\pm$ 5.91
Cz	high	young	137.45 $\pm$ 7.53	140.91 $\pm$ 3.64	123.27 $\pm$ 7.28
		old	152.36 $\pm$ 4.13	152.91 $\pm$ 3.50	148.18 $\pm$ 3.75
	low	young	131.45 $\pm$ 6.73	143.45 $\pm$ 4.71	146.00 $\pm$ 7.75
		old	158.18 $\pm$ 3.55	162.36 $\pm$ 4.91	169.64 $\pm$ 6.07
O1/O2	high	young	150.18 $\pm$ 4.64	153.45 $\pm$ 4.66	135.64 $\pm$ 7.12
		old	158.36 $\pm$ 4.10	162.00 $\pm$ 2.68	162.73 $\pm$ 5.63
	low	young	154.91 $\pm$ 3.89	155.09 $\pm$ 5.78	156.36 $\pm$ 5.04
		old	170.00 $\pm$ 3.82	160.73 $\pm$ 3.56	164.73 $\pm$ 5.63
P3/P4	high	young	145.82 $\pm$ 4.56	144.18 $\pm$ 3.24	132.91 $\pm$ 6.79
		old	154.18 $\pm$ 4.38	156.36 $\pm$ 2.01	164.00 $\pm$ 5.35
	low	young	149.64 $\pm$ 4.72	150.00 $\pm$ 2.71	154.00 $\pm$ 4.97
		old	164.00 $\pm$ 2.97	162.36 $\pm$ 2.75	165.45 $\pm$ 6.64
P7/P8	high	young	149.45 $\pm$ 4.68	149.64 $\pm$ 3.55	135.64 $\pm$ 7.38
		old	158.36 $\pm$ 3.59	161.64 $\pm$ 2.60	164.36 $\pm$ 4.90
	low	young	155.82 $\pm$ 4.39	152.55 $\pm$ 4.71	155.45 $\pm$ 5.55
		old	167.09 $\pm$ 2.82	167.27 $\pm$ 3.17	165.09 $\pm$ 7.04
T7/T8	high	young	146.18 $\pm$ 5.23	143.82 $\pm$ 4.23	134.73 $\pm$ 6.50
		old	154.91 $\pm$ 6.35	160.73 $\pm$ 2.29	161.45 $\pm$ 6.23
	low	young	157.09 $\pm$ 6.02	152.73 $\pm$ 4.33	155.82 $\pm$ 6.41
		old	161.27 $\pm$ 4.36	169.64 $\pm$ 3.34	162.18 $\pm$ 7.58



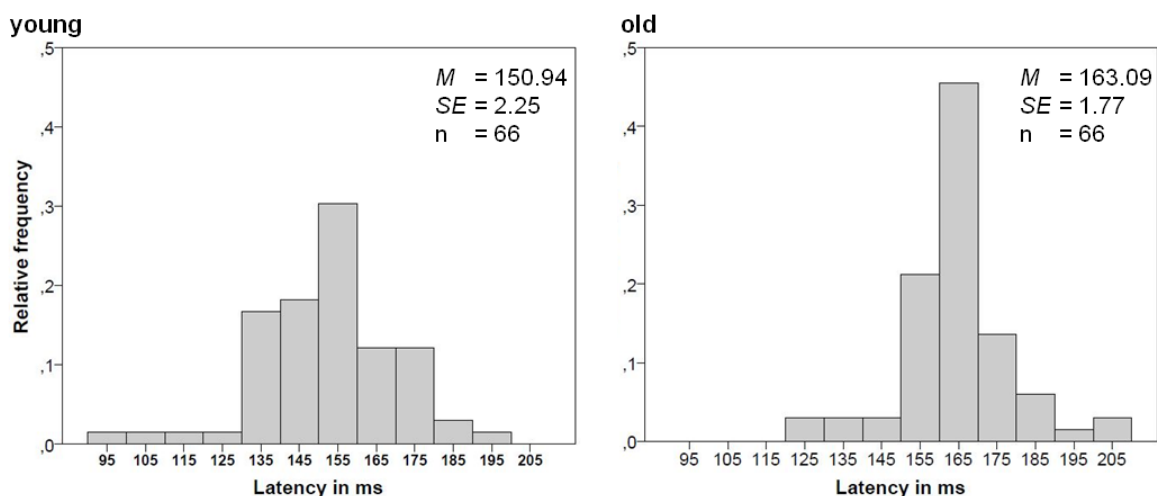
**Tab.6.** Amplitudes of the P150 in the difference wave AV (A+V)+X for each age group, SOA, and stimulus intensity. The amplitudes (in  $\mu\text{V}$ ) are shown as means  $\pm$  standard errors (for young and old:  $n = 11$ ).

Electrode	Intensity	Age	SOA		
			-50	0	+50
Pz	high	young	$3.74 \pm 0.87$	$4.03 \pm 1.10$	$2.95 \pm 1.04$
		old	$3.81 \pm 0.48$	$4.19 \pm 0.65$	$2.69 \pm 0.78$
	low	young	$5.19 \pm 1.05$	$3.88 \pm 0.81$	$4.24 \pm 1.13$
		old	$3.39 \pm 0.67$	$3.76 \pm 0.43$	$3.42 \pm 1.51$
Cz	high	young	$0.03 \pm 0.65$	$0.05 \pm 0.71$	$1.08 \pm 0.59$
		old	$1.26 \pm 0.36$	$1.83 \pm 0.29$	$1.23 \pm 0.34$
	low	young	$1.86 \pm 0.99$	$0.50 \pm 0.72$	$1.68 \pm 0.82$
		old	$1.36 \pm 0.38$	$1.08 \pm 0.21$	$1.21 \pm 0.41$
O1/O2	high	young	$6.91 \pm 0.79$	$6.64 \pm 1.02$	$5.02 \pm 0.57$
		old	$5.87 \pm 0.74$	$5.90 \pm 0.93$	$4.05 \pm 0.95$
	low	young	$7.84 \pm 1.39$	$6.34 \pm 0.78$	$5.49 \pm 0.94$
		old	$5.71 \pm 0.88$	$6.28 \pm 0.74$	$5.42 \pm 0.63$
P3/P4	high	young	$4.48 \pm 0.85$	$4.35 \pm 0.98$	$3.32 \pm 0.84$
		old	$3.89 \pm 0.37$	$4.22 \pm 0.60$	$2.53 \pm 0.69$
	low	young	$5.31 \pm 1.02$	$4.40 \pm 0.81$	$4.23 \pm 0.95$
		old	$4.00 \pm 0.70$	$3.92 \pm 0.52$	$3.54 \pm 0.50$
P7/P8	high	young	$4.91 \pm 0.67$	$4.46 \pm 0.84$	$3.68 \pm 0.64$
		old	$3.58 \pm 0.41$	$3.89 \pm 0.59$	$2.05 \pm 0.73$
	low	young	$5.83 \pm 1.13$	$4.99 \pm 0.86$	$4.06 \pm 1.00$
		old	$4.39 \pm 0.70$	$4.44 \pm 0.46$	$3.41 \pm 0.54$
T7/T8	high	young	$2.01 \pm 0.40$	$1.95 \pm 0.46$	$1.78 \pm 0.75$
		old	$1.41 \pm 0.33$	$1.10 \pm 0.21$	$0.66 \pm 0.41$
	low	young	$3.18 \pm 0.88$	$2.59 \pm 0.60$	$1.96 \pm 0.84$
		old	$1.08 \pm 0.45$	$2.07 \pm 0.39$	$1.49 \pm 0.46$



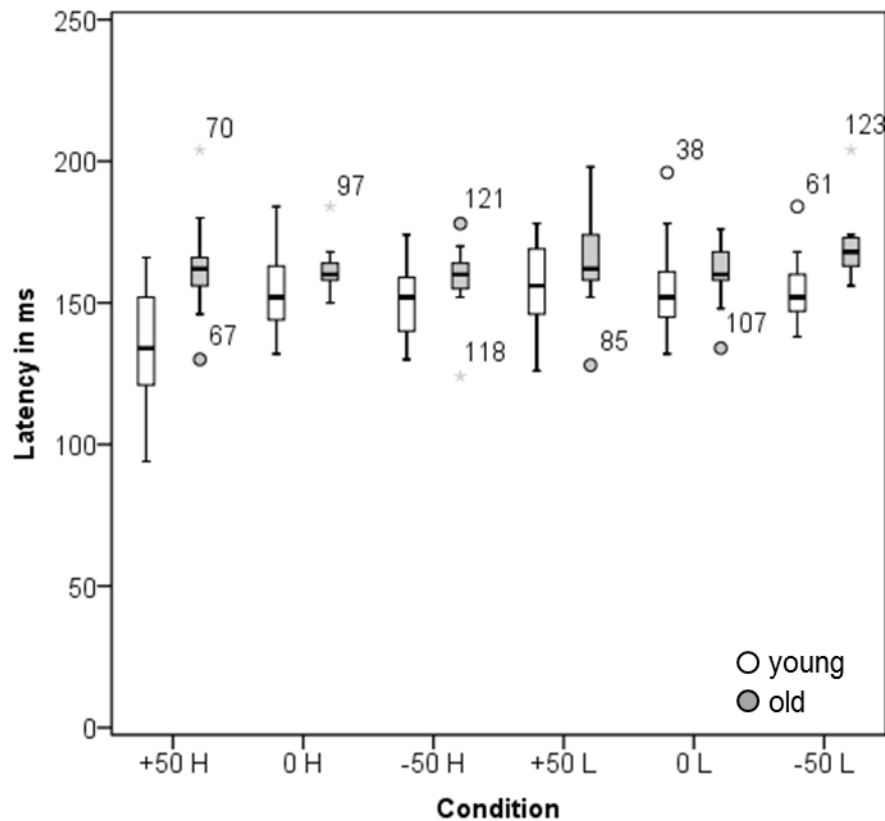
**Fig.25.** Amplitudes of the audiovisual interaction component P150 at each of the six electrode groups. The amplitudes are shown as means  $\pm 1.96$  standard errors (SE). By the example of the difference wave at an SOA of -50 ms at high intensity, it could be seen that, for both age groups, the amplitude decreased from the electrode group O1/O2 to the electrode groups P3/P4, P7/P8, and Pz to the electrode groups T7/T8 and Cz.

The Kolmogorov-Smirnov test for one sample was used to verify that the latencies of the P150 are normally distributed for both age groups. The test revealed violation of the normal distribution assumption for the elderly age group ( $p < 0.005$ ), whereas no evidence against the latencies of the young age group being normally distributed was found ( $p = 0.097$ ; see **Fig.26**). Because of the fact that the ANOVA is robust against violations of the normal distribution, it may be used under the premise that Mauchly's test of sphericity is not violated ( $p > 0.05$ ). And even if Mauchly's test becomes significant, a Greenhouse-Geisser correction could be applied in reporting the  $p$  values.

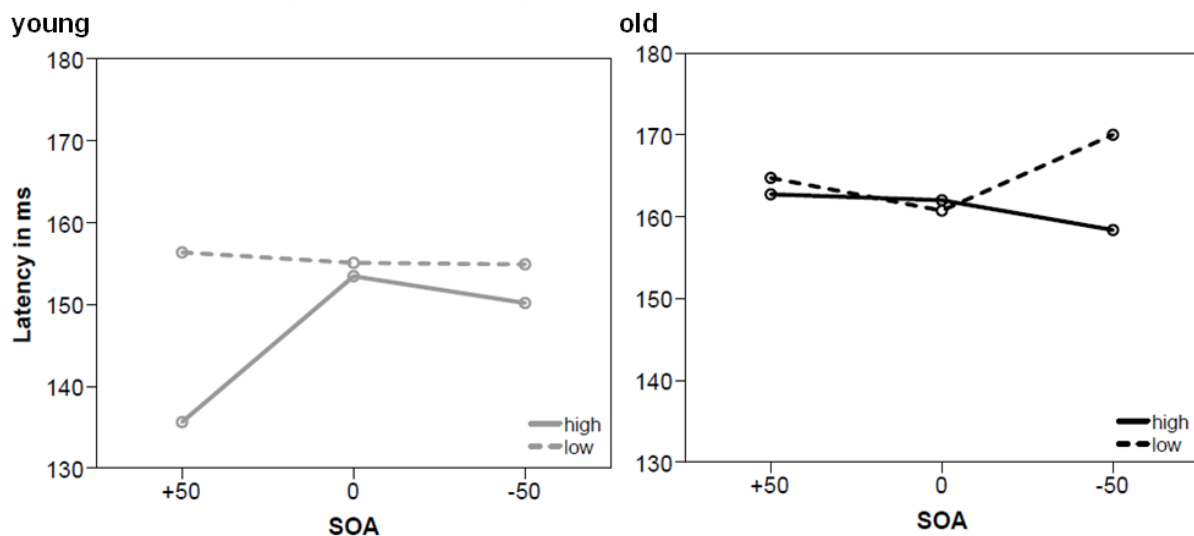


**Fig.26.** Distribution of the latencies of the P150 for the young (left) and the elderly age group (right).

To investigate whether stimulus intensity or SOA had a general influence on the latency of the P150 between the two age groups (Hypothesis 6), an ANOVA was conducted. **Fig.27** illustrates the latencies of the P150 for both stimulus intensities and age groups. Across the two intensity levels, the latency became shorter with increasing stimulus intensity, as reflected by a significant main effect of the factor 'Stimulus Intensity' ( $F(1,20) = 6.77$ ,  $p < 0.02$ ). The factor 'SOA' failed to reach significance ( $F(2,19) = 0.66$ ,  $p = 0.52$ ), indicating that the SOA had no general influence on the latency of the P150. Young adults had shorter latencies as compared to the elderly adults, as reflected by the between-subject effect 'Age' ( $F(1,20) = 7.98$ ,  $p = 0.01$ ). The second order interaction between the factors 'Stimulus Intensity', 'SOA', and 'Age' became significant ( $F(2,19) = 3.52$ ,  $p < 0.04$ ; see **Fig.28**), corresponding to the notion that for high stimulus intensity, the latency decreased from an SOA of +50 to 0 to -50 ms for the elderly age group, whereas the younger age group showed longest latency for an SOA of 0 ms followed by shorter latencies for an SOA of -50 and +50 ms. For low stimulus intensity, younger adults showed similar latencies for all of the three SOAs, whereas the elderly adults showed the shortest latency for an SOA of 0 ms, followed by an SOA of +50 and -50 ms.



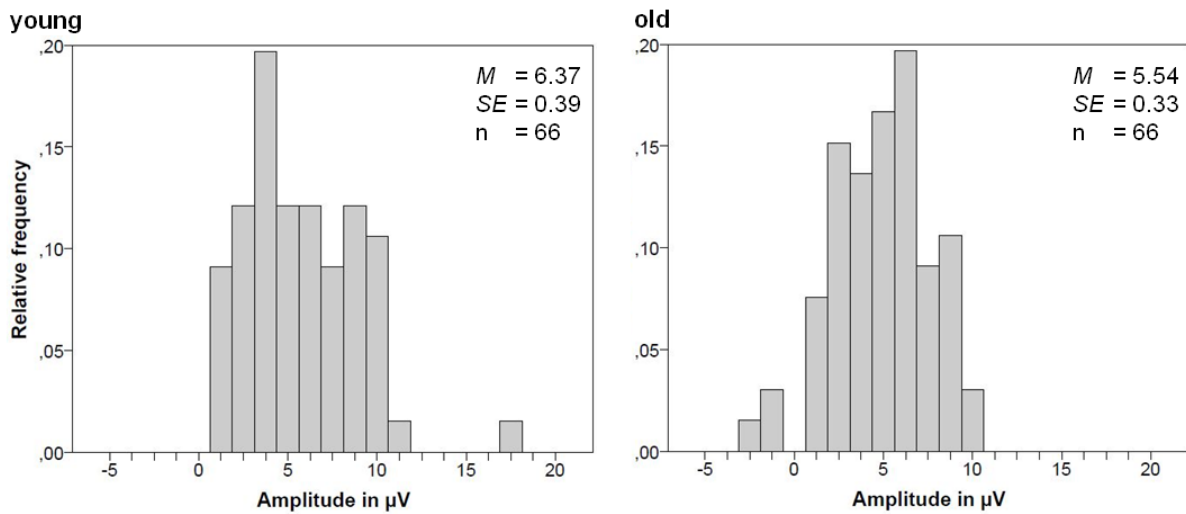
**Fig.27.** Effects of the stimulus intensity and the SOA on the latency of the P150 in young and elderly adults. The box plot displays the median, the first and the third quartile defining the box, and the 1.5 interquartile range of the lower and the upper quartile as whiskers. Young adults had shorter latencies as compared to elderly adults. Comparing the latencies for different stimulus intensities, the latencies decreased with increasing stimulus intensity (Outlier: +50 H: 67: subject 'S51', value: 130 ms; 70: subject 'S55', value: 204 ms; 0 H: 97: subject 'S60', value: 184 ms; -50 H: 118: subject 'S59', value: 6.28 ms; 121: subject 'S62', value: 178 ms; +50 L: 85: subject 'S59', value: 128 ms; 0 L: 38: subject 'S06', value 196 ms; 107: subject 'S59', value: 134 ms; -50 L: 61: subject 'S07', value: 184 ms; 123: subject 'S52', value: 204 ms).



**Fig.28.** Profile plot corresponding to the second order interaction between the factors 'Stimulus Intensity', 'SOA', and 'Age' in the ANOVA testing the latencies of the P150.

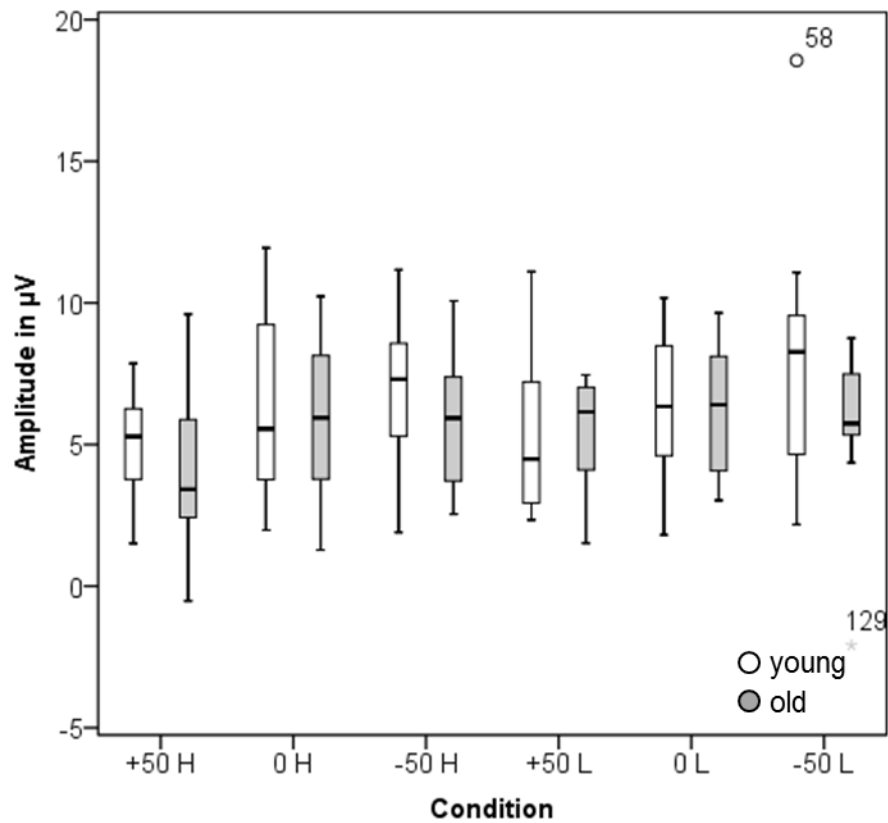
To probe whether the amplitude of the P150 is normally distributed for both age groups, a Kolmogorov-Smirnov test was conducted. The test revealed no violation of the normal

distribution assumption for the young ( $p = 0.098$ ) and the elderly age group ( $p = 0.2$ , see **Fig.29**).



**Fig.29.** Distribution of the amplitudes of the P150 for the young (left) and the elderly age group (right).

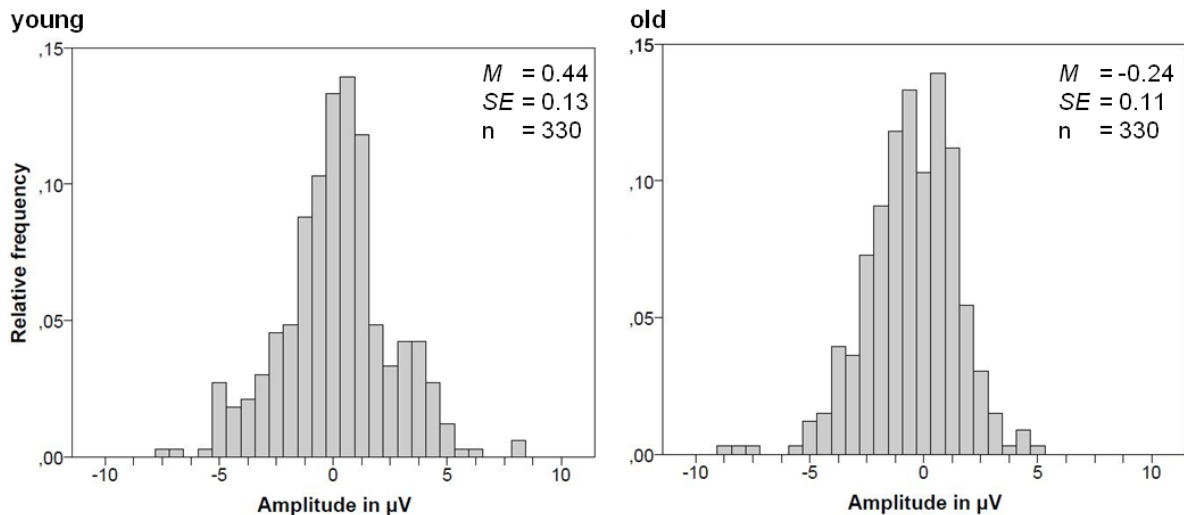
In the next step, a second ANOVA was conducted to investigate whether the stimulus intensity or the SOA had a general influence on the amplitude of the P150 between the two age groups (Hypothesis 6). As reflected by the significant main effect of the factor 'SOA' ( $F(2,19) = 8.45$ ,  $p = 0.001$ ), the amplitude increased from an SOA of +50 to 0 to -50 ms. Both factors 'Stimulus Intensity' ( $F(1,20) = 0.79$ ,  $p = 0.39$ ) and 'Age' ( $F(1,20) = 0.79$ ,  $p = 0.39$ ) failed to reach significance, indicating that neither the intensity of the stimulus nor the age had a general influence on the amplitude (**Fig.30**).



**Fig.30.** Effects of the stimulus intensity and the SOA on the amplitude of the P150 in young and elderly adults. The box plot displays the median, the first and the third quartile defining the box, and the 1.5 interquartile range of the lower and the upper quartile as whiskers. Amplitudes did not differ between the age groups, but decreased from an SOA of -50 to 0 to +50 ms (Outlier: -50 L: 58: subject 'S04', value: 18.56  $\mu V$ ; 129: subject 'S59', value: -2.09  $\mu V$ ).

### Early audiovisual interactions from 40 to 90 ms

The Kolmogorov-Smirnov test for one sample was used to verify that the amplitudes for both age groups are normally distributed. The test revealed violation of the normal distribution assumption (young age group:  $p < 0.008$ ; elderly age group:  $p < 0.027$ ; see **Fig.31**). Here, again an ANOVA was used to analyze the data, with the note that a Greenhouse-Geisser correction is applied in reporting the  $p$  value, if Mauchly's test of sphericity is violated.



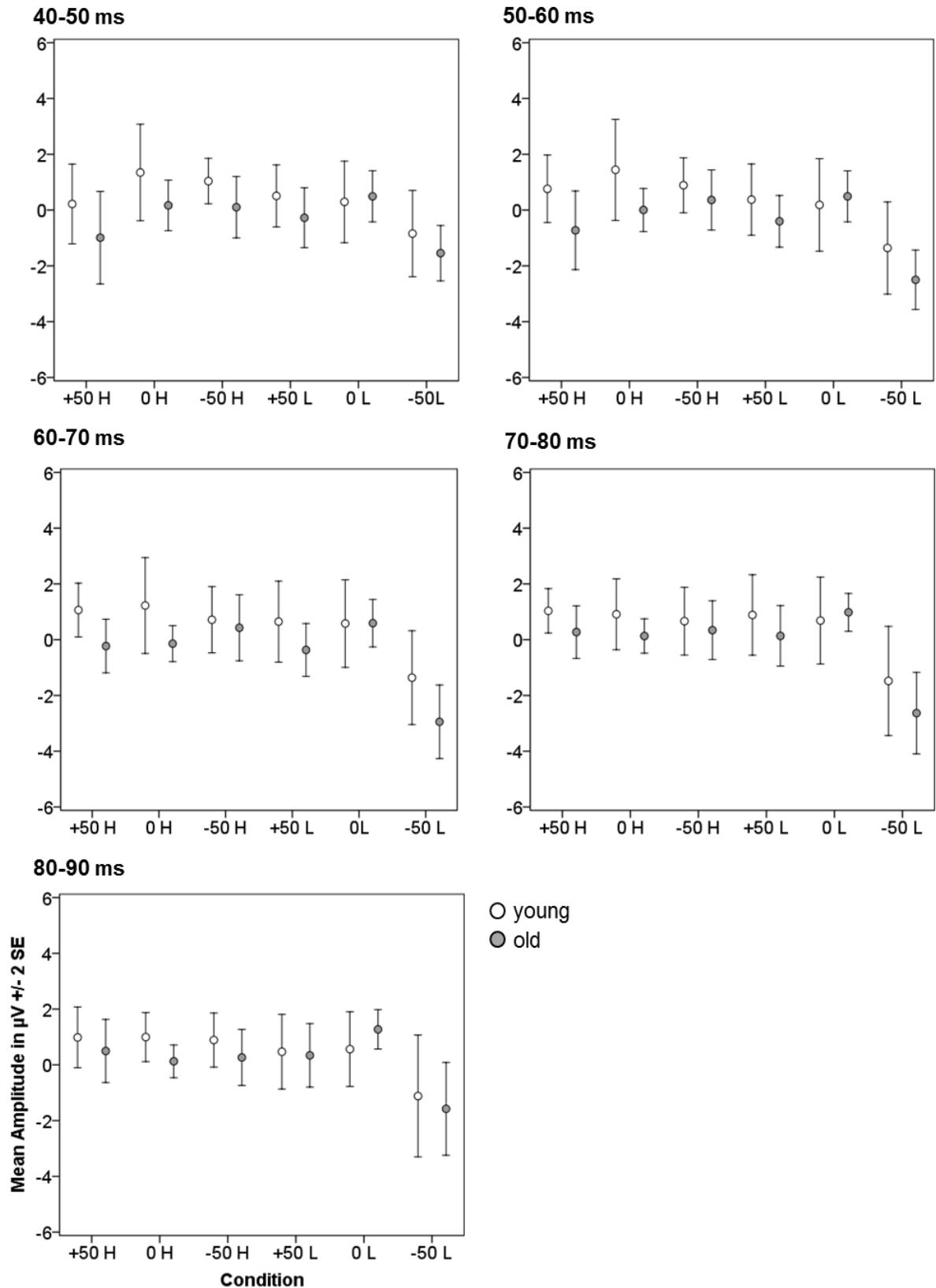
**Fig.31.** Distribution of the amplitudes of the early multisensory interaction for the young (left) and the elderly age group (right).

**Tab.7** shows the mean amplitudes for the early audiovisual interactions between 40 and 90 ms, divided into five time bins. For the analysis of the early multisensory interactions, an ANOVA was conducted to investigate whether stimulus intensity, SOA or time bin had a general influence on the amplitude (Hypothesis 7). **Fig.32** presents the effects of the SOA and the stimulus intensity on the amplitude of the early interactions within the five time bins. The significant main effect of the factor 'Stimulus Intensity' ( $F(1,20) = 5.35$ ,  $p < 0.04$ ), saying that the amplitude of the early multisensory interaction increased with increasing stimulus intensity, could be reduced only to the SOA of -50 ms. Furthermore, the main effect of the factor 'SOA' reached significance ( $F(2,19) = 8.71$ ,  $p < 0.001$ ). Again, this main effect could be ascribed to the SOA of -50 ms. The interaction between the two main factors 'Stimulus Intensity' and 'SOA' became significant ( $F(2,19) = 14.71$ ,  $p < 0.001$ ; see **Fig.33**), corresponding to the notion that this interaction was due to differences in the amplitudes for both stimulus intensities at an SOA of -50 ms. The factor 'Time Bin' revealed no significance, indicating that the amplitude of the early multisensory interactions did not differ between the time bins. Young and elderly adults were not significantly different in their amplitude of the early multisensory interactions, suggested by the between-subject factor 'Age' ( $F(1,20) = 1.724$ ,  $p = 0.20$ ).

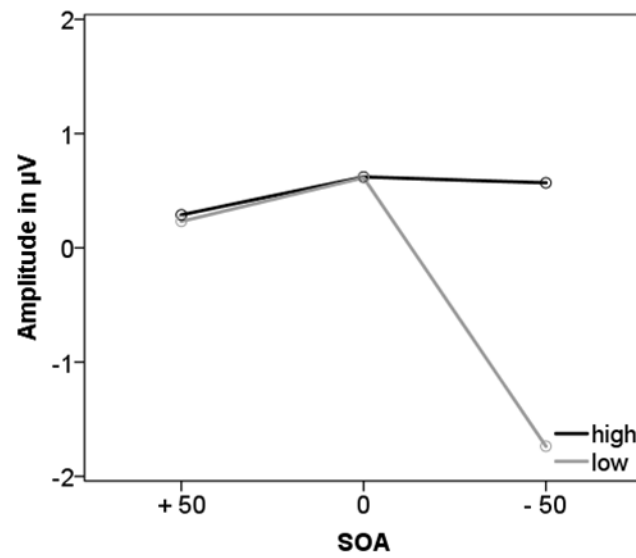
**Tab.7.** Amplitudes of the early audiovisual interactions for each of the five time bins at each SOA, stimulus intensity, and for both age groups. The amplitudes (in  $\mu\text{V}$ ) are shown as means  $\pm$  standard errors (for young and old:  $n = 11$ ).

Time bin	Intensity	Age	SOA		
			-50	0	50
40-50	high	young	$1.04 \pm 0.41$	$1.35 \pm 0.86$	$0.22 \pm 0.72$
		old	$0.10 \pm 0.55$	$0.17 \pm 0.45$	$-0.99 \pm 0.83$
	low	young	$-0.84 \pm 0.77$	$0.29 \pm 0.73$	$0.51 \pm 0.56$
		old	$-1.55 \pm 0.50$	$0.49 \pm 0.46$	$-0.28 \pm 0.54$
50-60	high	young	$0.89 \pm 0.49$	$1.44 \pm 0.90$	$0.76 \pm 0.61$
		old	$0.36 \pm 0.54$	$0.00 \pm 0.39$	$-0.73 \pm 0.71$
	low	young	$-1.36 \pm 0.83$	$0.19 \pm 0.83$	$0.37 \pm 0.64$
		old	$-2.50 \pm 0.53$	$0.49 \pm 0.56$	$-0.40 \pm 0.46$
60-70	high	young	$0.72 \pm 0.59$	$1.22 \pm 0.86$	$1.06 \pm 0.48$
		old	$0.43 \pm 0.59$	$-0.14 \pm 0.32$	$-0.23 \pm 0.48$
	low	young	$-1.36 \pm 0.84$	$0.58 \pm 0.79$	$0.65 \pm 0.73$
		old	$-2.95 \pm 0.66$	$0.59 \pm 0.43$	$-0.37 \pm 0.47$
70-80	high	young	$0.66 \pm 0.61$	$0.91 \pm 0.64$	$1.04 \pm 0.40$
		old	$0.34 \pm 0.53$	$0.13 \pm 0.31$	$0.27 \pm 0.47$
	low	young	$-1.48 \pm 0.98$	$0.69 \pm 0.78$	$0.89 \pm 0.72$
		old	$-2.63 \pm 0.73$	$0.98 \pm 0.34$	$0.14 \pm 0.54$
80-90	high	young	$0.89 \pm 0.48$	$0.99 \pm 0.44$	$0.98 \pm 0.54$
		old	$0.27 \pm 0.50$	$0.13 \pm 0.29$	$0.50 \pm 0.57$
	low	young	$-1.12 \pm 1.09$	$0.56 \pm 0.67$	$0.47 \pm 0.67$
		old	$-1.58 \pm 0.83$	$1.27 \pm 0.35$	$0.34 \pm 0.57$





**Fig.32.** Effects of the stimulus intensity and the SOA on the amplitude within the five time bins for young and elderly adults. Separately for each time bin, the amplitudes were shown as means  $\pm 2$  standard errors (SE). The amplitude of the early multisensory interactions increased with SOA and stimulus intensity, but did not show a difference between the age groups.

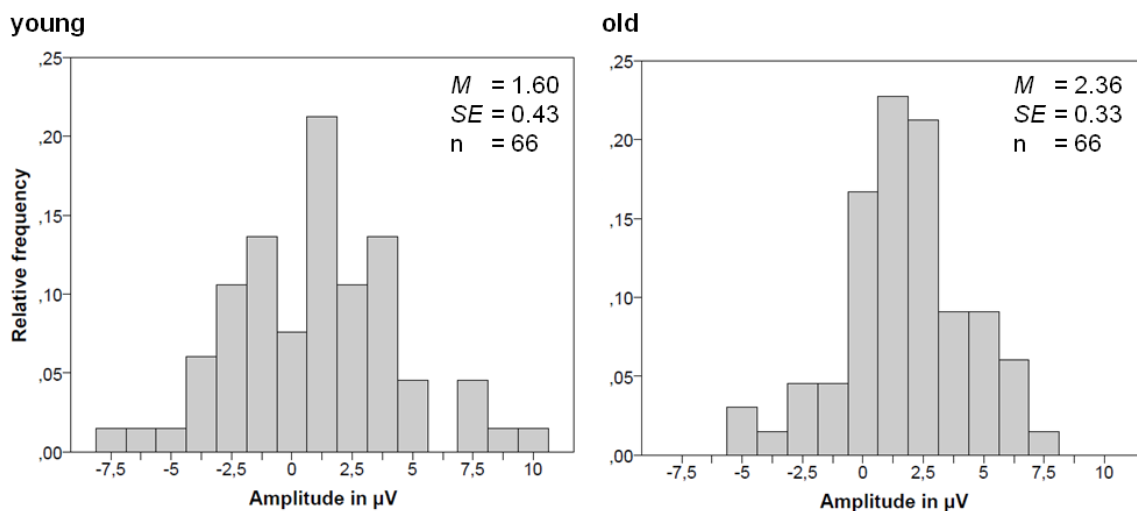


**Fig.33.** Profile plot corresponding to the interaction between the factors 'Stimulus Intensity' and 'SOA' in the ANOVA testing the amplitudes of the early multisensory interactions.

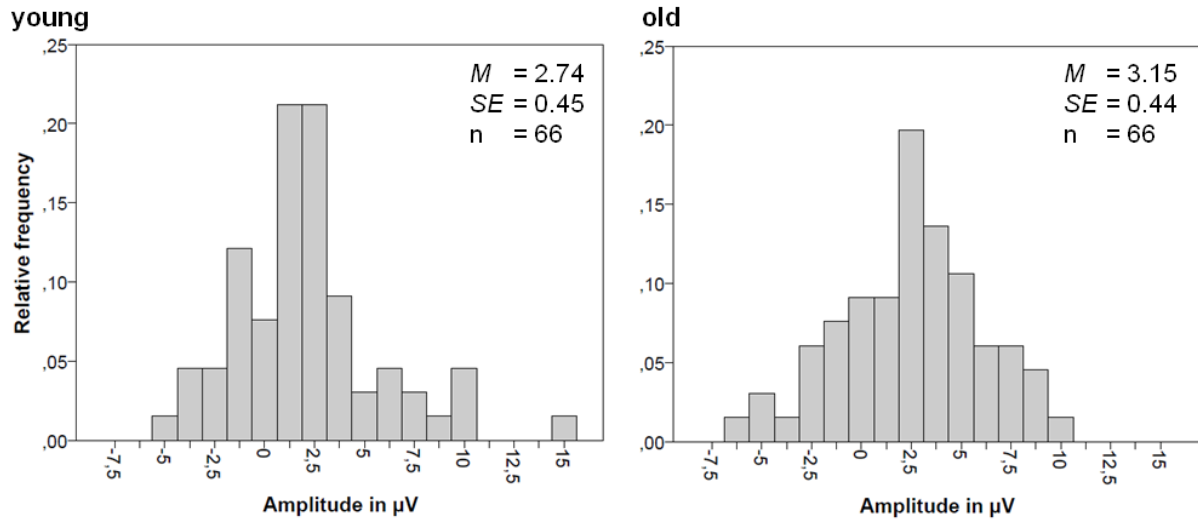
### Later audiovisual interactions at 215 and 255 ms

Post-hoc, on the basis of **Fig.24**, it could be supposed that young and elderly adults differed regarding their audiovisual interaction. A possible assumption is that elderly adults had kind of a standby potential, which is characterized by a more positive amplitude for the N215. In comparison to the elderly age group, the young adults exhibited a considerably lower amplitude for the N215. In addition, both age groups seemed to have similar amplitudes in the P255, indicating that the elderly adults performed likewise the younger adults.

The Kolmogorov-Smirnov test for one sample was used to verify that the latencies of the N215 and the P255 are normally distributed for both age groups. In case of the N215, the Kolmogorov-Smirnov test revealed no violation of the normal distribution assumption for the young ( $p = 0.2$ ) and the elderly age group ( $p = 0.2$ ; see **Fig.34**). In addition to that, the test revealed that the amplitudes of the P255 were not normally distributed for the young age group ( $p < 0.002$ ), whereas the amplitudes of the elderly age group were suggested normality ( $p = 0.2$ , see **Fig.35**).



**Fig.34.** Distribution of the amplitudes of the N215 for the young (left) and the elderly age group (right).

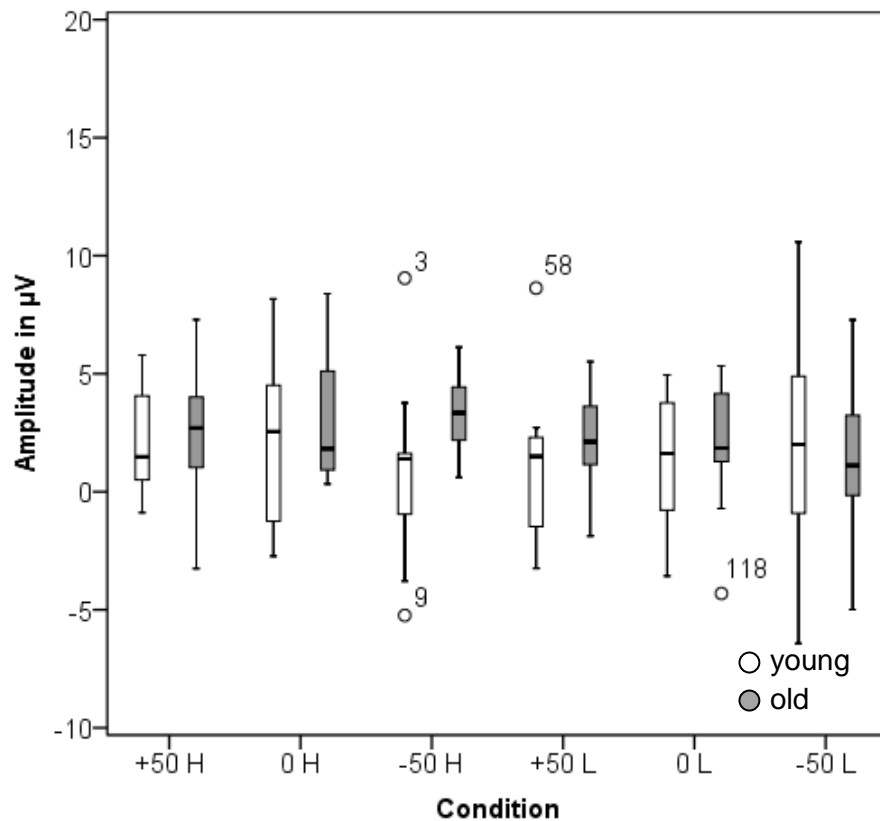


**Fig.35.** Distribution of the amplitudes of the P255 for the young (left) and the elderly age group (right).

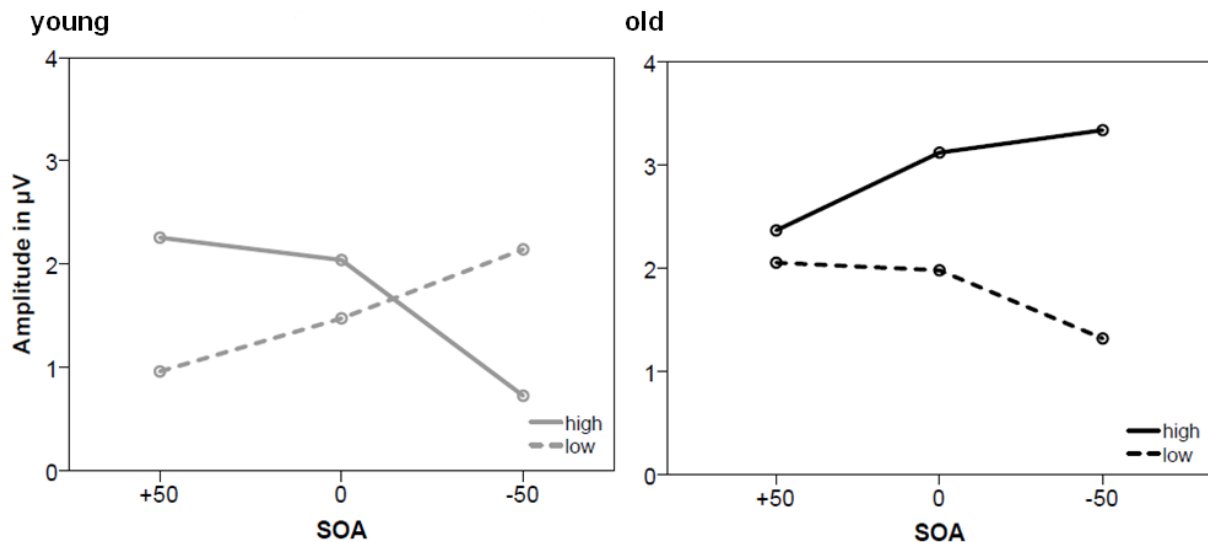
**Tab.8** shows the mean amplitudes of the N215 for each of the six difference waves at low and high intensity and for both age groups. To investigate if stimulus intensity or SOA had a general influence on the amplitude of the N215, an ANOVA was conducted. **Fig.36** illustrates the effects tested in the ANOVA. None of the main effects of the factors reached significance, indicating that neither the intensity, nor the SOA, nor the age had a general influence on the amplitude of the N215. Thus, the presumption that young and elderly adults differ in the amplitude of the N215, indicating a possible standby potential in the elderly age group, could not be confirmed. Only the second order interaction 'Stimulus Intensity \* SOA \* Age' became significant ( $F(1.68) = 3.71$ ,  $p = 0.04$ , Greenhouse-Geisser corrected), corresponding to the notion that, for the low stimulus intensity, the amplitude decreased for elderly subjects from an SOA of +50 to 0, and, finally, to -50 ms, whereas it increased for the young adults. For the high stimulus intensity, the amplitudes for both age groups were similar at an SOA of +50 ms. With an SOA from +50 to 0 to -50 ms the amplitude for the younger age group decreased, whereas it increased for the elderly age group (see **Fig.37**).

**Tab.8.** Amplitudes of the N215 for each SOA, stimulus intensity, and for both age groups. The amplitudes (in  $\mu V$ ) are shown as means  $\pm$  standard errors (for young and old:  $n = 11$ ).

Intensity	Age	SOA		
		-50	0	+50
high	young	$0.73 \pm 1.15$	$2.04 \pm 1.06$	$2.26 \pm 0.70$
	old	$3.34 \pm 0.56$	$3.12 \pm 0.89$	$2.37 \pm 0.88$
low	young	$2.14 \pm 1.53$	$1.48 \pm 0.83$	$0.96 \pm 0.99$
	old	$1.32 \pm 0.99$	$1.98 \pm 0.84$	$2.05 \pm 0.72$



**Fig.36.** Effects of the SOA and the stimulus intensity on the amplitude of the N215. The box plot displays the median, the first and the third quartile defining the box, and the 1.5 interquartile range of the lower and the upper quartile as whiskers (Outlier: -50 H: 3: subject 'S04', value: 9.05  $\mu V$ ; 9: subject 'S10', value: -5.24  $\mu V$ ; +50 L: 58: subject 'S04', value: 8.63  $\mu V$ ; 0 L: 118: subject 'S59', value: -4.31).



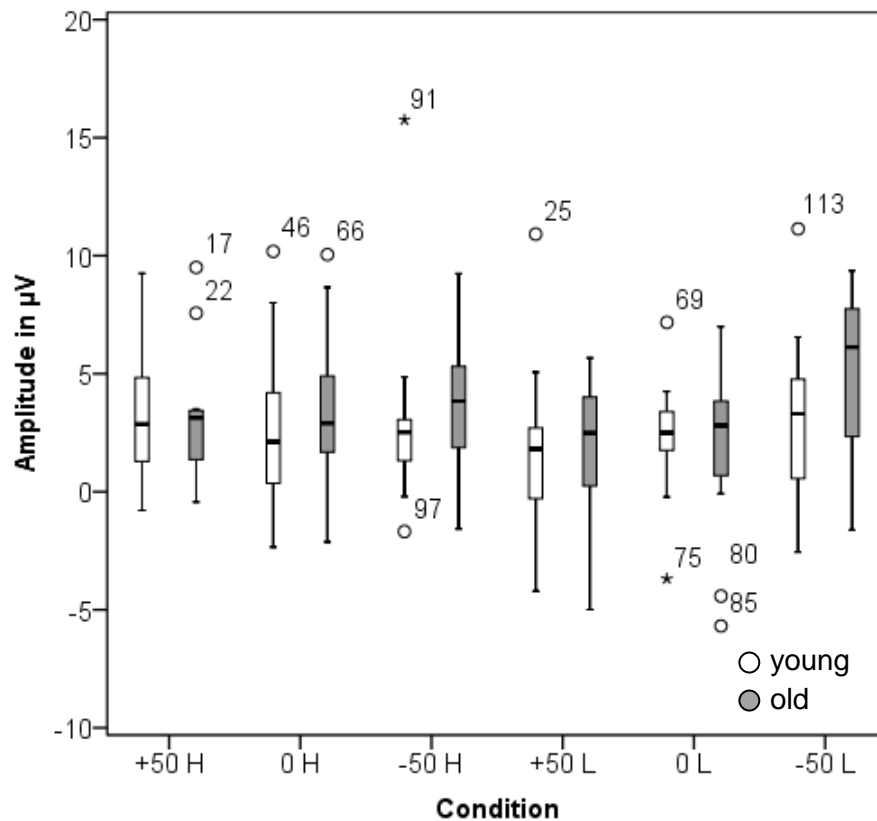
**Fig.37.** Profile plot corresponding to the interaction between the factors 'Stimulus Intensity', 'SOA', and 'Age' in the ANOVA, testing the amplitudes of the N215.

To test for the influence of stimulus intensity and SOA on the amplitude of the P255 between the age groups, an additional ANOVA was computed. **Tab.9** shows the mean amplitudes of the P255 for each of the six difference waves, both stimulus intensities and both age groups. **Fig.38** shows the effects of the SOA and the stimulus intensity on the

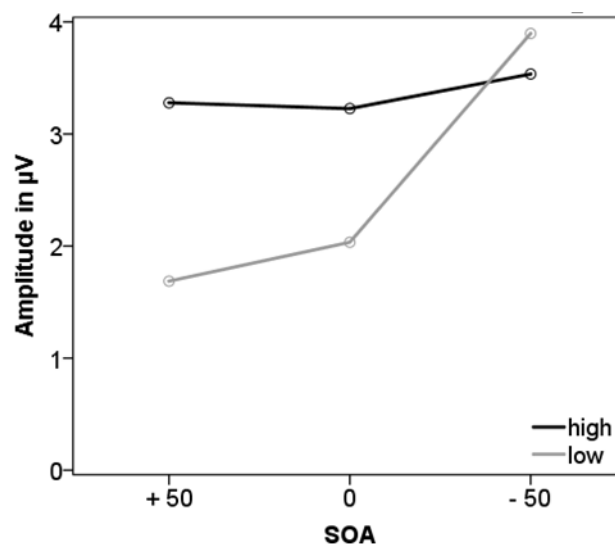
amplitude of the P255. Across the three SOAs, the amplitude for the P255 increased from +50 to 0 to -50 ms. This was revealed by the significant main effect of the factor 'SOA' ( $F(2,19) = 4.15$ ,  $p < 0.03$ ), which could be attributed to the low stimulus intensity. Neither the factor 'Stimulus Intensity', nor the factor 'Age' became significant. Thus, the presumption that young and elderly adults performed similarly could be confirmed. The interaction between the two main effects 'SOA' and 'Stimulus Intensity' reached significance ( $F(2,19) = 3.89$ ,  $p < 0.03$ ), meaning that for low stimulus intensity, the amplitude showed a strong decrease from an SOA of -50 ms to 0 to +50 ms, while the amplitude was similar at each SOA for the high intensity (see **Fig.39**).

**Tab.9.** Amplitudes of the P255 for each SOA, stimulus intensity, and for both age groups. The amplitudes (in  $\mu V$ ) are shown as means  $\pm$  standard errors (for young and old:  $n = 11$ ).

Intensity	Age	SOA		
		-50	0	+50
high	young	3.18 $\pm$ 1.36	2.88 $\pm$ 1.11	3.33 $\pm$ 0.96
	old	3.89 $\pm$ 0.92	3.57 $\pm$ 1.07	3.23 $\pm$ 0.91
low	young	2.98 $\pm$ 1.20	2.31 $\pm$ 0.82	1.78 $\pm$ 1.21
	old	4.82 $\pm$ 1.21	1.76 $\pm$ 1.17	1.60 $\pm$ 1.04



**Fig.38.** Effects of the SOA and the stimulus intensity on the amplitude of the P255. The box plot displays the median, the first and the third quartile defining the box, and the 1.5 interquartile range of the lower and the upper quartile as whiskers (Outlier: +50 H: 17: subject 'S57', value: 9.51  $\mu V$ ; 22: subject 'S62', value: 7.57  $\mu V$ ; 0 H: 46: subject 'S03', value: 10.18  $\mu V$ ; 66: subject 'S62', value: 10.05  $\mu V$ ; -50 H: 91: subject 'S04', value: 15.75  $\mu V$ ; 97: subject 'S10', value: -1.68  $\mu V$ ; +50 L: 25: subject 'S04', value: 10.91  $\mu V$ ; 0 L: 69: subject 'S04', value: 7.18  $\mu V$ ; 75: subject 'S10', value -3.69  $\mu V$ ; 80: subject 'S54', value: -4.42  $\mu V$ ; 85: subject 'S59', value: -5.69  $\mu V$ ; -50 L: 113: subject 'S04', value: 11.14  $\mu V$ ).



**Fig.39.** Profile plot corresponding to the interaction between the factors 'Stimulus Intensity' and 'SOA' in the ANOVA testing the amplitudes of the P255.

### 4.3. Discussion

This event-related potential study was designed to investigate age-related differences in multisensory integration. A FAP task with no demand for any manual response was conducted using unimodal auditory, unimodal visual, and bimodal audiovisual stimuli with varying stimulus intensities and SOAs. Difference waves  $AV-(A+V)+X$  were computed for each SOA and each stimulus intensity to examine audiovisual interaction. Three latency regions were of special interest, the focus being on audiovisual interactions in the latency range between 100 and 200 ms. In addition, audiovisual interactions in short (40-90 ms) and long (215 and 255 ms) latency ERPs were examined. We found that the latency of the positive audiovisual interactions component P150 was affected by age and stimulus intensity, whereas the amplitude of this component was only influenced by the SOA. Early audiovisual interactions showed no age-related differences, but varied with stimulus intensity and SOA. Post-hoc analysis of the late components of audiovisual interactions obtained no difference between the age groups.

#### Audiovisual interactions from 100 to 200 ms

Audiovisual interaction occurred at about 150 ms after stimulus-onset of the visual stimulus and was most prominent over occipital sites. The latency of the focused P150 component increased for both age groups with increasing stimulus intensity, but elderly adults exhibited longer latencies in comparison to young adults for all SOAs. In contrast to the latency, the amplitude of the P150 was not affected by age and intensity but increased from an SOA of +50 to 0 to -50 ms.

Positive values in the  $AV-(A+V)+X$  difference wave were due to smaller amplitudes (absolute values) of the potential elicited by the bimodal stimulus type (AV) than in the sum of the potentials elicited by unimodal auditory and unimodal visual stimulus types (A+V). The timing and the topography of the observed audiovisual interaction was consistent with those of the visual N1 (150 ms), elicited by the unimodal visual stimulus. Considering the notion that ERPs prior to 200 ms poststimulus are linked to activity in modality specific pathways (Giard & Peronnet, 1999), this interaction seems to occur in the visual pathway. The finding of an audiovisual interaction in the time range around 150 ms is consistent with previous studies that investigated multisensory interaction in young adults with a RTP task. Giard and Peronnet (1999) were one of the first, who reported a similar audiovisual interaction over occipital sites at 155-200 ms. Furthermore, a study by Molholm et al. (2002) revealed audiovisual interaction at 160-180 ms over occipito-temporal areas, which was also reported by Teder-Sälejärvi et al. (2002). Giard and Peronnet (1999) suggested that interaction in this



latency range might reflect a reduction of the visual evoked N1, which is generated in the extrastriate cortex (Mangun, 1995) and has been functionally associated with visual discrimination processes (Vogel & Luck, 2000). They further suggested that the auditory stimulus modulates the activity of the visual system. At the neuronal level of audiovisual integration, it could be possible that less energy is required from the visual system for processing a visual stimulus with a simultaneously presented auditory stimulus compared with visual processing without an auditory stimulus (Giard & Peronnet, 1999). Thus, a decrease in the amplitude of the visual N1 during audiovisual stimulus processing could reveal facilitatory processing within the extrastriate cortex, which in turn provides electrophysiological support to behavioral studies finding the “facilitation effect” (Giard & Peronnet, 1999). In addition to an ERP analysis by computing the simple difference wave AV-(A+V), Teder-Sälejärvi et al. (2002) localized the source of the observed interaction by dipole modeling. Indeed, the inferior occipital cortex was indicated as a source of audiovisual interaction by this dipole analysis (Teder-Sälejärvi et al., 2002).

The present results obtained an increase in the latency of the audiovisual interaction component P150 for the elderly adults relative to their young counterparts. This observed prolongation in the latency could likely be attributed to age-related changes in ERPs elicited by unimodal stimuli. Over the past decades, visual and auditory evoked potentials were used to investigate the effect of age on the visual and auditory system and to demonstrate slowing with age (Ball et al., 1989; Bashore, 1989; Brown et al., 1983; Marsh et al., 1990). According to Bashore (1989), the timing of ERPs could be conducive to identify the focus of the decrease in processing speed in a more precise way. Previous studies obtained age-related differences in visual (Celesia et al., 1987; Celesia & Daly, 1977) and auditory evoked potentials (Anderer et al., 1996). Moreover, regarding the visual N1, which might be responsible for the observed latency differences in the present study, latency has been reported to increase with age (Díaz & Amenedo, 1998; Falkenstein et al., 2006; Kolev et al., 2006; Yordanova et al., 2004). Allison et al. (1984) suggested that degenerative changes in the visual system manipulate the neural basis of potentials such as the visual N1. These degenerative changes in the visual system could arise in all stages reaching from the perception to the processing of a visual stimulus (Nusbaum, 1999). Thus, for example, a reduced amount of retinal ganglion cells (Curcio & Drucker, 1993; Gao & Hollyfield, 1992) or a loss in the number of axons in the optic nerve (Dolman et al., 1980; Repka & Quigley, 1989) could account for a reduced latency in the visual N1, which in turn helps to explain the observed age-related latency differences in the audiovisual interaction component P150 in the current study.

With varying stimulus intensity, this study showed latency differences for the audiovisual interaction component P150. Latency of P150 was shortest for stimuli with high intensities.

These observed latency changes could, similar to the aforementioned age-related differences, be attributed to ERPs elicited by unimodal stimuli. Stimulus intensity has been found to have an impact on the latency of visual (Bobak et al., 1987; Morrison & Reilly, 1989) and auditory evoked potentials (Polich, 1989; Sugg & Polich, 1995), which parallels behavioral results reporting RTs decreasing with increasing stimulus intensity for unimodal (Bell et al., 2001; Diederich & Colonius, 2004a; Rach et al., 2011; Senkowski et al., 2011) and bimodal stimuli (Rach et al., 2011; Senkowski et al., 2011). Specifying the case of the visual N1, which had the same latency range and topography as the observed audiovisual interaction component P150, Lines et al. (1984) reported shorter latencies to bright compared to dim stimuli (154.8 and 160.9 ms, respectively). Thus, the observed decrease in the latency of the component P150 at high intensities may be attributable to the shorter latency of N1 elicited by a visual stimulus of high intensity. The stimulus intensity may first affect the latency of the visual N1, which in turn affects the latency of the P150 in the difference wave.

Besides the fact that the young adults exhibited shorter P150 latencies than elderly adults, two special conditions must be noted, in which the age groups differ more saliently. First, in bimodal stimulus types with high intensities where the visual stimulus precedes the auditory stimulus (SOA +50 ms), young adults had a distinctly shorter latency relative to the elderly adults (136 ms for the young and 163 ms for the elderly age group). A second considerable difference between the age groups was obtained for bimodal stimuli at low intensities where the auditory stimulus precedes the visual stimulus by 50 ms. Here again, latency of the young adults was about 15 ms shorter than the latency of the elderly adults (155 and 170 ms, respectively).

The amplitude of the audiovisual interaction component P150 was not affected by age or stimulus intensity but changed with SOA. The results of the present study show that the amplitude increased from +50 to 0 to -50 ms, which means that highest amplitudes were obtained for bimodal stimuli where the auditory stimulus precedes the visual stimulus by 50 ms. This result could provide an electrophysiological correlate of the decrease in RT (and SRT) with SOA decreasing from +50 to -50 ms, observed in studies by Diederich and colleagues (Diederich et al., 2008; Diederich & Colonius, 2008). According to the TWIN model for FAP tasks (Diederich & Colonius, 2004b), the non-target stimulus has to win the race in the first peripheral stage to open the time window of integration. If the target stimulus falls into this given time window of constant duration, crossmodal interaction will be elicited. When the target stimulus wins the race in the first stage, no crossmodal interaction will take place (Diederich et al., 2008). Diederich et al. (2008) postulated that SOA does not influence the amount of interaction but the probability of interaction, which, in turn, determines the expected amount of crossmodal interaction on SOA. For large SOAs, the probability of

interaction is small, whether the target or the non-target is presented first (Diederich et al., 2008). The chance for the non-target to win the race and to open the window decreases if it is presented late relative to the target (positive SOA). In addition, if the non-target precedes the target by a large SOA (negative SOA), the window, which is opened by the winning non-target, might be closed before the arrival of the target (Diederich et al., 2008). Specifying the influence of the SOA on the probability of interaction, Diederich et al. (2008) found that the probability of interaction decreases from negative SOAs (-100, -50 ms) to positive SOAs (+50 ms) within the TWIN model explanation. In case of the present study, this could mean that the probability of interaction, and thus the amplitude of the P150, is higher when the auditory non-target stimulus is presented before the visual target. This may help to explain the current results showing higher amplitudes for negative SOAs compared to positive SOAs.

Turning to possible brain areas that could be involved in the processing of audiovisual stimuli with temporal synchrony or asynchrony, Bushara et al. (2001) hypothesized that temporally defined audiovisual interactions could be mediated by the insular cortex. Their positron emission tomography (PET) study obtained a large neural network of insular and several brain regions, such as posterior-parietal, prefrontal, and cerebellar areas, to be activated during the detection of asynchronous audiovisual stimuli. Moreover, they found interactions between the insula, the posterior thalamus, and the superior colliculus.

### **Early audiovisual interactions from 40 to 90 ms**

Early audiovisual interactions were investigated in the latency range of 40 to 90 ms at occipital sites. Mean amplitudes of audiovisual interactions in this latency range were not affected by age, but revealed an influence by stimulus intensity and SOA. The observed differences in the amplitude due to stimulus intensity or SOA could be ascribed only to the SOA of -50 ms (see below).

The timing and the topography of the early audiovisual interactions observed in the present study is consistent with those of the visual evoked C1 (75 ms), which is thought to reflect initial activation of the visual cortex by a visual stimulus (Cobb & Dawson, 1960). The finding of early audiovisual interaction in the time range of 40-90 ms at occipital sites is consistent with the results of previous studies, investigating multisensory interaction in young adults. A similar audiovisual interaction at parieto-occipital sites was reported by Giard and Peronnet (1999), who found interaction to occur between 40 and 90 ms. Additionally, Molholm et al. (2002) revealed early audiovisual interaction with the same topography in a latency range of 46-66 ms. In line with this, Fort et al. (2002b) observed interaction at occipital sites within 45-85 ms latency. Furthermore, several other studies also confirmed the

timing and topography of the early audiovisual interaction observed in this current study (Cappe et al., 2010; Van der Burg et al., 2011; for review, see De Meo et al., 2015), indicating that initial activation of the primary visual cortex (earliest visual evoked potential C1 at around at 45-60 ms, Clark et al., 1995; Clark & Hillyard, 1996) and audiovisual effects could occur at about the same time. Molholm et al. (2002) pointed out that early audiovisual interaction with the same timing and topography as the visual C1 is consistent with modifications of very early sensory processing by an attached auditory stimulus. Thus, this leads to the suggestion that the early visual cortex is the source of the audiovisual interaction between 40 and 90 ms observed here.

Possible brain regions involved in contributing to early audiovisual interactions caused a debate over the last decades. Whether early audiovisual interaction originates in visual (Fort et al., 2002b; Molholm et al., 2002), auditory (Vidal et al., 2008) or both cortices (Raij et al., 2010; Senkowski et al., 2007; Teder-Sälejärvi et al., 2002), did not seem to be clear, but Cappe et al. (2010) resolved this debate with a source estimation. They identified sources that contributed to interactions within a network including primary visual (V1) and primary auditory cortices (A1) as well as the posterior superior temporal sulcus (STS). Due to faster transmission times within the auditory system (23 ms in human; Raij et al., 2010), auditory responses could begin prior the arrival of the visual response in all of the previously mentioned regions (Cappe et al., 2010). Macaque studies by Falchier et al. (2002) and Rockland and Ojima (2003) provided evidence for direct projections from both primary auditory cortex and auditory association areas to both primary and secondary visual cortex, which were considered as a combination of feedforward and feedbackward projections (Cappe et al., 2010). Thus, the aforementioned results of previous studies support our suggestion that the visual cortex is involved in early audiovisual interaction, but precise neurophysiologic mechanisms that underlie early audiovisual interactions remain largely unknown.

The current study revealed differences in the mean amplitude of early audiovisual interaction with varying stimulus intensity and SOA. Besides the fact that early audiovisual interaction was observed for all bimodal stimulus types, the amplitude differences could only be interpreted when considering the combined influence of stimulus intensity and SOA. For all combinations of stimulus intensity and SOA, the mean amplitude was in a similar range. A decline in the amplitude occurred only for the special case of bimodal stimuli at low intensity with an SOA of -50 ms. Based on this observation, two possible explanations arise: First, due to the fact that the amplitude was most prominent for an SOA of -50 ms, it could be suggested, according to the TWIN model (Diederich et al., 2008), that the probability of early interaction and thus the amplitude (absolute value) of the early interaction component is higher if the auditory non-target is presented before the visual target. This explanation is

consistent with our above mentioned suggestion on amplitude differences with SOA for the audiovisual interaction component P150. Second, for the special case of an SOA of -50 ms, it could be suggested that early audiovisual interaction occurred most robustly when the presented bimodal stimulus was at low intensity compared to high intensity. This would be in line with Senkowski et al. (2011), who found early multisensory interaction to occur most prominently when the simultaneously presented stimuli were at low intensity (40 dB), indicating that early multisensory interaction follows the principle of inverse effectiveness. Taken together, the increased probability of early interaction for an SOA of -50 ms and the link to the principle of inverse effectiveness may help to explain the amplitude differences observed in the current study.

The lack of age-related changes in early multisensory interaction could be ascribed to the visually evoked C1, which is likely to be generated in the striate cortex (Gomez Gonzalez et al., 1994; Jeffreys & Axford, 1972). Early VEPs like the C1 reflect the initial activation of the visual cortex (Cobb & Dawson, 1960). Allison et al. (1984) reported that the amplitude of the visual C1 only decreases during childhood and adolescence, but that no developmental changes occur thereafter. These results may account for the missing age-related differences in early audiovisual interactions in this study. It could be possible that the neural substrate of the early VEP C1 is less affected by age-related degenerative changes in the visual system than later potentials (visual N1, see above).

### **Later audiovisual interactions at 215 and 255 ms**

Post-hoc, the differences in the performance of young and elderly adults were examined in terms of later audiovisual interactions at occipital sites. Amplitude differences in the negative audiovisual interaction component N215 led to this post-hoc analysis. It seemed that elderly adults had some kind of a “standby” potential, which was expressed by a more positive N215 amplitude in comparison to the young adults. In relation to the apparently differences in the N215, the positive interaction component P255 was investigated, for which the performance of both age groups seemed to be similar again.

According to the N215 amplitude, no clear or consistent influence of age on the performance was observed, but in comparison with stimulus intensity and SOA the following picture emerges: Amplitudes were smaller for young compared to elderly adults for all SOAs at high intensity. Starting at an SOA of +50 ms, the amplitude for the young decreased to an SOA of -50 ms, whereas it increased for the elderly. Thus at high intensity, age-related difference in amplitude was largest when the auditory non-target was presented before the visual target. Referred to low stimulus intensity, amplitudes of the audiovisual interaction

component N215 increased from +50 to 0 to -50 ms for young adults, whereas it decreased for elderly adults. Hence, young adults exhibited smaller amplitudes for SOAs of +50 and 0 ms, while elderly adults showed smaller amplitudes for an SOA of -50 ms. Taken together, no clear pattern of age-related differences in the performance could be observed in case of the N215, indicating that the suggested “standby” potential does not exist in the observed latency range of later audiovisual interaction. Furthermore, investigation of the positive audiovisual interaction component P255 revealed no age-related difference in the amplitude, but stimulus intensity and SOA had a combined influence on the amplitude. For high stimulus intensity, the amplitude was similar at each SOA, whereas the amplitude showed a distinct increase from an SOA of +50 to 0 to -50 ms for low stimulus intensity.

The post-hoc suggestion that elderly adults have a performance different from young adults could not be confirmed. The lack of a clear pattern of age-related differences seems likely to indicate that no “standby” potential exists in elderlys’ performance in audiovisual interaction in a later latency range.

### **Conclusion (EEG experiment)**

The present electrophysiological data are in general agreement with those reported by previous studies finding audiovisual interactions in early and mid-range latencies at occipital sites in young adults (Fort et al., 2002a; Giard & Peronnet, 1999; Molholm et al., 2002; Teder-Sälejärvi et al., 2002). In addition to former studies, the current study focused on the effect of age on audiovisual interaction. The results show that young and elderly adults differ only in the mid-range latency interactions at around 150 ms as indicated by differences in the latencies, while no age-related differences were obtained for early and late interactions. Degenerative changes in the visual system, which could arise at all stages reaching from the perception to the processing of a visual stimulus (Nusbaum, 1999), may account for such age-related changes in audiovisual interaction. Besides the considerable amount of behavioral studies investigating age-related differences in multisensory integration, further electrophysiological studies examining this issue are clearly needed.

## 5. Summary and conclusion

The purpose of the present study was to investigate the mechanisms of audiovisual integration in young and elderly adults. Since to date, to our knowledge, no studies exist considering the age-related audiovisual integration performance with an electrophysiological approach, the aim was to bridge this gap. On that account, an initial reaction time experiment and two subsequent EEG experiments using unimodal auditory, unimodal visual, and bimodal audiovisual stimuli were conducted.

To obtain data on age-related changes in multisensory integration missing in the EEG literature, the initial idea was to replicate a study by Senkowski et al. (2011) assessing audiovisual integration in young adults and to extend this study to the point that a young and an elderly age group were tested, in order to compare the integration mechanisms available in the different age groups. The study by Senkowski and colleagues (2011) already comprised changing parameter stimulus intensity, whose possible influences should be assessed here as well. In spite of the fact that all stimuli were equal in form, size, and intensities to those used by Senkowski et al. (2011), it was not possible to attain the same results in our replication (Experiment 2). Visual stimuli consisting of Gabor patches, which were also used in the study by Senkowski et al. (2011), were not sufficient to elicit the expected VEPs in each of the 24 participants. This led us to believe that a Gabor patch was not the optimal type of stimulus to elicit stable VEPs in the present study. Because of the fact that the auditory stimuli elicited stable AEPs in each participant, we decided to repeat the study with another type of visual stimulus (checkerboard). Hence, in Experiment 3, age-related changes in audiovisual integration could be reported for the first time with the use of an EEG experiment.

To test whether stimulus parameters like stimulus intensity or SOA have an additional influence on the audiovisual integration, the strategies of previous studies in the field of multisensory integration were extended by this aspect. In each of the three experiments, both unimodal and bimodal stimuli were presented with different stimulus intensities and, in addition, in Experiments 1 and 3 bimodal stimuli were presented with varying SOAs.

The behavioral experiment (Experiment 1) revealed that elderly adults react slower to unimodal stimuli than their young counterparts. Despite elderly's deficits in the processing of unimodal stimuli, it is striking that elderly perform equally well in processing bimodal stimuli. While elderly adults also exhibited slightly longer RTs to bimodal stimuli, however, RTs did not differ significantly between the age groups. This result is supported by a similar amount of MRE in both age groups. Contrary to the initial assumption, elderly adults did not benefit more from a stimulus presentation containing stimuli from two different sensory modalities,

but showed a similar performance as compared to young adults. In relation to these RT results, the analysis of the EEG data (Experiment 3) revealed that elderly adults had longer latencies for the audiovisual integration component P150, indicating that elderly adults need more time to integrate information across different modalities than young adults. Linking the results of the Experiment 1 with those of Experiment 3, an opposing picture emerges: In the RT experiment, young and elderly adults seemed to act similarly to bimodal stimuli, whereas elderly adults seemed to need more time for the integration of audiovisual stimuli in the EEG experiment. A trend towards slower RTs to bimodal stimuli was observed for the elderly in the RT experiment as well, however, this did not reach significance.

Testing for an additional influence of stimulus intensity, the results showed decreasing RTs with increasing stimulus intensity for both unimodal and bimodal stimuli. This trend is also consistent with the EEG experiment (Experiment 3), showing shorter latencies for stimuli of high as compared to stimuli of low intensity.

Regarding the influence of SOA on audiovisual integration, it is conspicuous that RT was shortest to bimodal stimuli where the auditory non-target was presented with a large SOA (-100 ms) before the visual target. RT then decreased to bimodal stimuli with small SOA (-50 ms, A before V) and, finally, to bimodal stimuli with no SOA. Moreover, the percentage of MRE decreased in the same manner from bimodal stimuli presented with a large negative SOA (-100 ms) to those presented with no SOA. This trend was confirmed by the data of the EEG experiment, showing that the amount of interaction, as represented by the amplitude of the component P150, is highest for bimodal stimuli where the auditory non-target was presented before the visual target (-50 ms).

To conclude, the combination of our behavioral and electrophysiological studies shows that age, as well as stimulus intensity and SOA, have a significant influence on the audiovisual integration mechanisms. In the future, additional studies investigating the impact of age on the audiovisual integration performance with an electrophysiological approach are clearly needed. Moreover, further studies should take into account possible changes in audiovisual integration caused by varying stimulus intensities (near or above threshold) or SOAs. Because of conflicting results existing in the field of age-related multisensory integration measured with RT, it would be interesting to examine the influence of task complexity and different task paradigms within the same experiment.



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## 7. Appendix

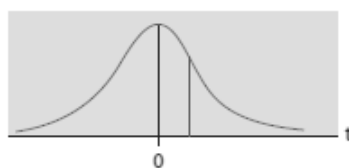
### I. Table J

$N \backslash k$	3 <sup>+</sup>	4 <sup>+</sup>	5 <sup>+</sup>	6 <sup>+</sup>	7 <sup>+</sup>	8 <sup>+</sup>	9
2 <sup>+</sup>	28	58	103	166	252	362	500
	–	60	106	173	261	376	520
3 <sup>+</sup>	41	84	150	244	370	532	736
	42	87	155	252	382	549	761
4 <sup>+</sup>	54	111	197	321	487	701	971
	55	114	204	331	501	722	999
5 <sup>+</sup>	66	137	244	397	603	869	1204
	68	141	251	409	620	893	1236
6 <sup>+</sup>	79	163	291	474	719	1037	1436
	81	167	299	486	737	1063	1472
7 <sup>+</sup>	91	189	338	550	835	1204	1668
	93	193	346	563	855	1232	1706
8 <sup>+</sup>	104	214	384	625	950	1371	1900
	106	220	393	640	972	1401	1940
9 <sup>+</sup>	116	240	431	701	1065	1537	2131
	119	246	441	717	1088	1569	2174
10 <sup>+</sup>	128	266	477	777	1180	1703	2361
	131	271	487	793	1205	1736	2407
11 <sup>+</sup>	141	292	523	852	1295	1868	2592
	144	298	534	869	1321	1905	2639
12 <sup>+</sup>	153	317	570	928	1410	2035	2822
	156	324	581	946	1437	2072	2872
13 <sup>+</sup>	165	343	615	1003	1525	2201	3052
	169	350	628	1022	1553	2240	3104
14 <sup>+</sup>	178	363	661	1078	1639	2367	3281
	181	376	674	1098	1668	2407	3335
15 <sup>+</sup>	190	394	707	1153	1754	2532	3511
	194	402	721	1174	1784	2574	3567
16 <sup>+</sup>	202	420	754	1228	1868	2697	3741
	206	427	767	1249	1899	2740	3798
17 <sup>+</sup>	215	445	800	1303	1982	2862	3970
	218	453	814	1325	2014	2907	4029
18 <sup>+</sup>	227	471	846	1378	2097	3028	4199
	231	479	860	1401	2130	3073	4260
19 <sup>+</sup>	239	496	891	1453	2217	3139	4428
	243	505	906	1476	2245	3240	4491
20 <sup>+</sup>	251	522	937	1528	2325	3358	4657
	256	531	953	1552	2350	3406	4722

**Table J** (from Bortz & Lienert, 2008). This table includes the critical  $L$  values for an  $\alpha = 0.05$  (upper value) and an  $\alpha = 0.01$  (bottom value). Whenever an observed  $L$  value for  $3 \leq k \leq 9$  and  $2 \leq N \leq 20$  reaches or exceeds the critical  $L$  value, the observed  $L$  value will reach significance at an  $\alpha$  % level. Values correspond to a one-sided test.



## II. Table X



Fläche* Fg	0,55	0,60	0,65	0,70	0,75	0,80	0,85
1	0,158	0,325	0,510	0,727	1,000	1,376	1,963
2	0,142	0,289	0,445	0,617	0,816	1,061	1,386
3	0,137	0,277	0,424	0,584	0,765	0,978	1,250
4	0,134	0,271	0,414	0,569	0,741	0,941	1,190
5	0,132	0,267	0,408	0,559	0,727	0,920	1,156
6	0,131	0,265	0,404	0,553	0,718	0,906	1,134
7	0,130	0,263	0,402	0,549	0,711	0,896	1,119
8	0,130	0,262	0,399	0,546	0,706	0,889	1,108
9	0,129	0,261	0,398	0,543	0,703	0,883	1,100
10	0,129	0,260	0,397	0,542	0,700	0,879	1,093
11	0,129	0,260	0,396	0,540	0,697	0,876	1,088
12	0,128	0,259	0,395	0,539	0,695	0,873	1,083
13	0,128	0,259	0,394	0,538	0,694	0,870	1,079
14	0,128	0,258	0,393	0,537	0,692	0,868	1,076
15	0,128	0,258	0,393	0,536	0,691	0,866	1,074
16	0,128	0,258	0,392	0,535	0,690	0,865	1,071
17	0,128	0,257	0,392	0,534	0,689	0,863	1,069
18	0,127	0,257	0,392	0,534	0,688	0,862	1,067
19	0,127	0,257	0,391	0,533	0,688	0,861	1,066
20	0,127	0,257	0,391	0,533	0,687	0,860	1,064
21	0,127	0,257	0,391	0,532	0,686	0,859	1,063
22	0,127	0,256	0,390	0,532	0,686	0,858	1,061
23	0,127	0,256	0,390	0,532	0,685	0,858	1,060
24	0,127	0,256	0,390	0,531	0,685	0,857	1,059
25	0,127	0,256	0,390	0,531	0,684	0,856	1,058
26	0,127	0,256	0,390	0,531	0,684	0,856	1,058
27	0,127	0,256	0,389	0,531	0,684	0,855	1,057
28	0,127	0,256	0,389	0,530	0,683	0,855	1,056
29	0,127	0,256	0,389	0,530	0,683	0,854	1,055
30	0,127	0,256	0,389	0,530	0,683	0,854	1,055
40	0,126	0,255	0,388	0,529	0,681	0,851	1,050
60	0,126	0,254	0,387	0,527	0,679	0,848	1,046
120	0,126	0,254	0,386	0,526	0,677	0,845	1,041
z	0,126	0,253	0,385	0,524	0,674	0,842	1,036

**Table X** (from Bortz & Lienert, 2008). Distribution function of the  $t$ -distribution.\* Area amount for the negative  $t$  values result from the relation  $p(-t_{Fg}) = 1 - p(t_{Fg})$

Continuation of Table X

0,90	0,95	0,975	0,990	0,995	0,9995	$t_{0,05}$	$t_{0,01}$
3,078	6,314	12,706	31,821	63,657	636,619	0,997	1,000
1,886	2,920	4,303	6,965	9,925	31,598	0,950	0,990
1,638	2,353	3,182	4,541	5,841	12,941	0,878	0,959
1,533	2,132	2,776	3,747	4,604	8,610	0,811	0,917
1,476	2,015	2,571	3,365	4,032	6,859	0,754	0,874
1,440	1,943	2,447	3,143	3,707	5,959	0,707	0,834
1,415	1,895	2,365	2,998	3,499	5,405	0,666	0,798
1,397	1,860	2,306	2,896	3,355	5,041	0,632	0,765
1,383	1,833	2,262	2,821	3,250	4,781	0,602	0,735
1,372	1,812	2,228	2,764	3,169	4,587	0,576	0,708
1,363	1,796	2,201	2,718	3,106	4,437	0,553	0,684
1,356	1,782	2,179	2,681	3,055	4,318	0,532	0,661
1,350	1,771	2,160	2,650	3,012	4,221	0,514	0,641
1,345	1,761	2,145	2,624	2,977	4,140	0,497	0,623
1,341	1,753	2,131	2,602	2,947	4,073	0,482	0,606
1,337	1,746	2,120	2,583	2,921	4,015	0,468	0,590
1,333	1,740	2,110	2,567	2,898	3,965	0,456	0,575
1,330	1,734	2,101	2,552	2,878	3,922	0,444	0,561
1,328	1,729	2,093	2,539	2,861	3,883	0,433	0,549
1,325	1,725	2,086	2,528	2,845	3,850	0,423	0,537
1,323	1,721	2,080	2,518	2,831	3,819	0,413	0,526
1,321	1,717	2,074	2,508	2,819	3,792	0,404	0,515
1,319	1,714	2,069	2,500	2,807	3,767	0,396	0,505
1,318	1,711	2,064	2,492	2,797	3,745	0,388	0,496
1,316	1,708	2,060	2,485	2,787	3,725	0,381	0,487
1,315	1,706	2,056	2,479	2,779	3,707	0,374	0,478
1,314	1,703	2,052	2,473	2,771	3,690	0,367	0,470
1,313	1,701	2,048	2,467	2,763	3,674	0,361	0,463
1,311	1,699	2,045	2,462	2,756	3,659	0,355	0,456
1,310	1,697	2,042	2,457	2,750	3,646	0,349	0,449
1,303	1,684	2,021	2,423	2,704	3,551	0,304	0,393
1,296	1,671	2,000	2,390	2,660	3,460	0,250	0,325
1,289	1,658	1,980	2,358	2,617	3,373	0,178	0,232
1,282	1,645	1,960	2,326	2,576	3,291		

**Continuation of Table X** (from Bortz & Lienert, 2008). Distribution function of the  $t$ -distribution.

\* Area amount for the negative  $t$  values result from the relation  $p(-t_{Fg}) = 1-p(t_{Fg})$