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Budapest University of Technology and Economics

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Cognitive aging and its modulatory factors:
A psychophysiological approach

Thesis Booklet

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Studies included in the thesis

Study 1A:

Nagy, B., Czigler, I., File, D., & Gaál, Zs. A. (2020). Can irrelevant but salient visual cues compensate for the age-related decline in cognitive conflict resolution? – An ERP study. *PLoS One, 15*(5), e0233496. https://doi.org/10.1371/journal.pone.0233496

Study 1B:

Gaál, Zs. A., Nagy, B., File, D., & Czigler, I. (2020). Older adults encode task-irrelevant stimuli, but can this side-effect be useful to them? *Frontiers in Human Neuroscience, 14*, 569614. https://doi.org/10.3389/fnhum.2020.569614

Study 2:

Nagy, B., Kojouharova, P., Protzner, A. B., & Gaál, Zs. A. (2024). Investigating the Effect of Contextual Cueing with Face Stimuli on Electrophysiological Measures in Younger and Older Adults. *Journal of Cognitive Neuroscience, 36*(5), 776-799. https://doi.org/10.1162/jocn_a_02135

Study 3:

Nagy, B., Protzner, A. B., van der Wijk, G., Wang, H., Cortese, F., Czigler, I., & Gaál, Zs. A. (2022). The modulatory effect of adaptive task-switching training on resting-state neural network dynamics in younger and older adults. *Scientific reports, 12*(1), 9541. https://doi.org/10.1038/s41598-022-13708-x

Introduction and main objectives

We live in an aging society where it is increasingly urgent to support the physiological, psychological and socio-economic functioning and well-being of older people for aiding their professional and everyday life to be more active and independent, and ultimately increasing their life quality. One of the main factors of aging is cognitive change, particularly in information processing, filtering, and extraction, which can be assessed through behavioural, psychophysiological, and neural measures.

The main purpose of this thesis was threefold. First, we investigated key cognitive and neural functions that are strongly affected by healthy (non-pathological) aging - such as cognitive control, inhibition (including specific processes like ignoring distracting information - perceptual inhibition, suppressing prepotent responses - response inhibition, resolving cognitive conflict - cognitive inhibition), attentional guidance (orientation and allocation), and general neural information processing capacity - in order to better understand the behavioural, electrophysiological, and neural dynamic mechanisms underlying cognitive aging. Second, we aimed to highlight compensatory mechanisms that support older adults' performance, including potential advantages of age-related cognitive changes (e.g., looser filtering of stimuli and increased distractor processing), enhanced reliance on relatively preserved functions (e.g., implicit learning of stimulus regularities), and the beneficial effects of intervention methods like cognitive training. Third, we examined these effects at three different levels: (1) within individual task trials, (2) across the progression of a task, and (3) in less task-specific and more intrinsic processing manner. We used electroencephalography (EEG) to detect age-related changes in cognitive processing, applying two methodological approaches: event-related potentials (ERPs), derived from averaging event-locked neural activity and providing correlates of specific cognitive processes; and neural dynamics measures, including multiscale entropy (MSE, reflecting signal variability and complexity) and spectral power density (SPD, reflecting oscillatory signal power).

Studies 1A and 1B used different analyses and datasets from the same experiment. In **Study 1B**, we investigated whether older adults process task-irrelevant but highly salient stimuli (e.g., faces) to a greater extent than younger adults and whether they can sufficiently encode and later retrieve such information. This study was based on the inhibitory deficit hypothesis of aging which posits that age-related declines in inhibitory control impair the suppression of irrelevant information, allowing it to enter and remain in working memory and thereby increasing distractibility and interference sensitivity (Hasher & Zacks, 1988; Hasher et al., 2007). At the same time, prior findings suggest that increased distractor processing may also benefit older adults by supporting the encoding and later use of previously irrelevant stimuli (e.g., Amer & Hasher, 2014; Biss et al., 2013; Rowe et al., 2006; Weeks et al., 2016).

In **Study 1A**, we examined age-related differences in inhibitory control using a modified Simon task (measuring stimulus-response conflict). Specifically, we investigated whether non-informative but salient gaze cues could guide visuospatial attention (as in the Posner paradigm; Frischen et al., 2007; Friesen et al., 2005; Posner, 1980; Posner & Cohen, 1984) and influence cognitive conflict monitoring, resolution, and motor response inhibition and evaluation - particularly in older adults. The design was inspired by van der Lubbe and Verleger (2002), who examined age-related behavioural and electrophysiological differences in stimulus-response conflict in a Simon-task, and by Cespón and his colleagues (2013), who introduced an additional perceptual conflict into a modified Simon task. Both studies found significant impairments in stimulus-response conflict resolution through decreased efficiency in visuospatial stimulus evaluation, response selection, and motor inhibition with aging.

In **Study 2**, we explored whether older adults can acquire and utilize environmental regularities (contextual cues) to improve performance, based on the assumption that reduced cognitive control may facilitate stimulus-driven implicit (statistical) learning and greater processing of irrelevant information in aging (Amer et al., 2016; Chrysikou et al., 2014). Using a visual search task, we measured contextual cueing, the guidance of visuospatial attention by the co-occurrence, spatial arrangement, and dynamics of objects at behavioural, electrophysiological, and neural dynamics levels across the progression of contextual learning (Chun, 2000). This study built on prior EEG research on contextual cueing (Johnson et al., 2007; Schankin & Schubö, 2009, 2010; Schankin et al., 2011; Zinchenko et al., 2020) and on earlier work from our lab (Kojouharova et al., 2023), which replicated the original spatial contextual cueing paradigm (Chun & Jiang, 1998) and extended it to include aging and EEG analysis. Here, we implemented a modified contextual cueing design with face stimuli and in addition we focused on neural dynamics underlying the formation of contextual representations.

In **Study 3**, we emphasized adaptive cognitive training as an intervention method, as its positive impact has been robustly found on enhancing cognitive functioning and delaying or mitigating age-related decline (e.g., Gates et al., 2011; Kelly et al., 2014; Lustig et al., 2009; Reijnders et al., 2013). Such compensatory effects are thought to arise from stimulating neural and cognitive plasticity which remains viable in healthy aging (Mahncke et al., 2006; Park & Bischof, 2013). We relied on our lab's longitudinal task-switching training dataset, which has already revealed training-related behavioural and electrophysiological changes in trained, near-transfer, and far-transfer tasks across age groups (Gaál & Czigler, 2018). Results indicated that older adults could reach performance levels comparable to younger adults following training, though improvements depended on task similarity and cognitive domain overlap. However, the primary goal of cognitive training is not merely to improve performance on trained or closely related tasks, but to induce broader cognitive and neural benefits. To address this, we analysed resting-state EEG from our training dataset to identify more general and task-independent effects of training on aging-related brain changes. We focused on measuring intrinsic neural dynamics and information processing capacity with MSE and SPD, which are considered indicators of the functional integrity, adaptability, and flexibility of the brain based on neural signal variability (e.g., Deco et al., 2011, 2013; Garrett et al., 2013; McIntosh et al., 2010). This approach was motivated by growing evidence of the age-related shift from global to local neural processing capacity and complexity, with implications for cognitive functioning, learning, and adaptability (McIntosh et al., 2014, 2019; Wang et al., 2016, 2018).

Thesis points and main findings

Thesis point 1: The inhibitory deficit hypothesis of cognitive aging is supported by less efficient information filtering through enhanced task-irrelevant visual stimuli processing and interference-sensitivity in older adults, however, they cannot benefit from these effects (Study 1A, Study 1B).

In Study 1B, we found age-related differences in early visual processing of unattended and task-irrelevant face stimuli, as reflected by decreased P1 and increased N170 amplitude in older compared to younger adults. These findings indicate greater attentional cost and visual engagement in the older age-group. Moreover, as found in Study 1A, the non-informative gaze direction of these task-irrelevant faces guided attention towards the target stimulus presented by the larger N2pc (posterior-contralateral N2) component in congruent compared to incongruent gaze condition, and enhanced the preliminary incorrect motor response activation in incongruent Simon condition by the increased positive dip of s-LRP (stimulus-locked lateralized readiness potential) component regardless of age. However, the added distraction only affected conflict resolution performance in older adults. More precisely, older adults' reaction time and error rate increased in trials with incongruent Simon condition where the irrelevant gaze directed towards the relevant stimulus. However, their performance was not facilitated in trials where the non-informative gaze directed towards the congruent Simon stimulus. Although older adults processed task-irrelevant stimuli more deeply than younger adults, they did not consolidate or retrieve this information effectively, as shown by lower discrimination indices and absence of a recollection-related ERP component (LPC – late positive component) in the old/new test. Overall, task-irrelevant stimuli affect visual and attentional processing, and increase interference in cognitive performance without offering compensatory benefits in the older age-group.

Thesis point 2: Inhibitory control functions also show age-related decline by less effective stimulus-response conflict evaluation, motor response selection and inhibition (Study 1A).

In Study 1A, we also found age-related differences in the behavioural and electrophysiological indexes in the processing of the Simon task. Older adults showed less efficient stimulus-response conflict resolution, motor response selection and inhibition, as well as higher decision threshold by increased behavioural Simon-effect (larger RT for incongruent compared to congruent trials), larger and delayed wrong-side (in incongruent Simon trials) and correct-side response activation and longer latency difference between these two s-LRP sub-processes compared to younger adults. Motor execution showed prolonged response preparation, indicated by an earlier and more pronounced r-LRP (response-locked LRP). Target evaluation was also less efficient in older adults, as detected by smaller and delayed P3b component. These results suggest that older adults require more cognitive resources and higher decision thresholds during conflict resolution.

Thesis point 3: The implicit learning of stimuli regularities and its supporting effect on visual search remains effective in older adults but the underlying neural and cognitive mechanism behind contextual learning show differences compared to younger adults (Study 2).

In Study 2 we investigated how our surroundings' regularities can be acquired in an implicit manner and if these repeated patterns can support performance in younger and older adults. A contextual cueing task was applied with repeated (same faces are presented together in the same spatial position) and new (randomly generated) configurations where the visual search task was to find the male face. Both age-groups could utilize these stimuli regularities in the visual search performance quite quickly (after 5 repetitions in younger and after 10 repetitions in older adults) with a similar strength as the contextual cueing effect (the RT difference/ratio between new and repeated trials) were comparable between the two age-groups. Additionally, these repeated configurations generated more global and streamlined representations and more deterministic information processing at local neural dynamics mainly at visuospatial and motor areas in both age-groups. This could be detected by the decreased finer timescale entropy (1-20 ms) and higher frequency band power (13-30 Hz) for repeated trials compared to new ones. However, contextual learning was supported by more efficient cognitive processing just in younger adults but not in older ones. The increased target-locked N2pc (attentional guidance to target) and P3b (intermediate target evaluation and stimulus-response linking) components in repeated compared to new configurations in the younger age-group emphasized the importance of the early attentional locus in contextual cueing. Nevertheless, implicit contextual information can be successfully utilized to bolster performance in older people but it is supported only by optimized local neural dynamics but not by more efficient cognitive processing.

Thesis point 4: Adaptive cognitive training is a suitable intervention method for gaining more general and widespread benefits by modulating age-related changes in intrinsic neural dynamics (Study 3).

In Study 3 we investigated age- and training-related changes in intrinsic information processing capacity by applying MSE and SPD methods on resting-state EEG data recorded before and after an adaptive task-switching training protocol with control and training groups from younger and older adults. Before training we detected the previously observed age-related shift from more global to local intrinsic neural dynamics: compared to the younger age-group older adults showed widespread decrease in coarse scale MSE (35-50 ms) and low frequency band power (1-7 Hz) connected to distributed information processing as well as widespread increase in fine timescale MSE (1-20 ms) and higher frequency band power (mainly between 15-30 Hz) relevant in local information processing dynamics. However, task-switching training established a general far-transfer effect in task-independent measures mainly in older adults through the modulation of age-related changes in resting-state brain dynamics. The old-training group presented increased coarse timescale entropy (20-50 ms) mainly at midline and right fronto-central areas, increased low frequency band power (3-7 Hz) mainly at midline and right centro-parietal areas, and increased alpha frequency band power (8-14 Hz) mainly at fronto-central areas after training which suggest the regained and increased reliance on large-scale information processing flexibility and neural adaptability. Additionally, increased fine timescale entropy (1-20 ms) was also detected to a lesser extent in the same group after training at midline and left fronto-central areas. In contrary, the young-training group showed only training-related changes in oscillatory power (increased lower frequency band power) but not in entropy measures which suggests that adaptive cognitive training had a greater, more complex and non-linear effect on the neural functioning of older adults.

General discussion

The main goal of the current thesis was twofold: (1) to deepen our understanding of the cognitive aging process by identifying more detailed behavioural, electrophysiological and neural correlates, and (2) to examine whether the observed age-related cognitive changes can be turned into advantages or successfully compensated for, thereby supporting more efficient functioning in older adults.

We found substantial evidence reaffirming the inhibitory deficit hypothesis of aging (Hasher & Zacks, 1988; Hasher et al., 2007). Older adults were less able to ignore distractor stimuli sufficiently as they processed them to a greater extent (Study 1B), and the task-irrelevant information (attentional guidance of the non-informative gaze cues) modulated their target processing and task performance more strongly compared to younger adults by increasing interference and cognitive resource demands (Study 1A). With respect to suppressing prepotent responses, older adults more readily activated available motor responses at the early stage of response selection and evaluation, and they appeared to require more neural evidence to select and execute motor responses (higher response threshold), suggesting insufficient motor response inhibition (Study 1A). Regarding cognitive conflict, stimulus-response conflict resolution was less efficient in older adults, as revealed by slower visuomotor processing and target evaluation, prolonged and increased decision thresholds, and slower performance which were amplified with increasing levels of stimulus-response conflict and interference as reflected in larger Simon-effect (Study 1A). We also emphasized that older adults can utilize implicitly acquired environmental regularities to support their performance in visual search similar to younger adults (Study 2). Furthermore, by examining resting-state neural dynamics, we provided further evidence for the age-related shift from large-scale to local information processing capacity and neural communication which may impact learning, adaptability and cognitive functioning in older adults (Study 3).

Despite older adults processed task-irrelevant stimuli more deeply and this affected their task performance, they were not encoded and consolidated into retrievable representations (Study 1B), contradicting previous positive findings (Amer & Hasher, 2014; Biss et al., 2013; Rowe et al., 2006; Weeks et al., 2016). A key difference is that in these studies, distracting information was relevant and intentionally processed during prior tasks, whereas in our study participants were instructed to ignore these distracting stimuli. Thus, we propose that successful consolidation of distracting information in older adults requires some degree of prior relevance or intentional processing. Regarding the effect of task-irrelevant information on performance, we observed increased interference in older adults when the non-informative gaze directed towards the target containing stimulus-response conflict (incongruent Simon trials), but we found no evidence for the facilitating side when the non-informative gaze directed towards the target without stimulus-response conflict (congruent Simon trials) (Study 1A). Taken together, looser filtering of stimuli only increased visuomotor conflict and interference in older adults without providing performance benefits.

As our results show in Study 2, contextual cueing remained effective with aging, though the supporting mechanisms showed age-related differences. Repeated presentations of co-occurring faces shaped more globally grouped and streamlined neural representations through repetition suppression and more deterministic and less variable local neural dynamics in both age-groups. However, more efficient cognitive processing of these repeated configurations were observed only in younger adults but not in older ones through enhanced attentional guidance and target evaluation, highlighting the importance of early attentional locus in contextual cueing (Goujon et al., 2015; Sisk et al., 2019; Wolfe & Horowitz, 2017). This age-related difference can be explained by the statistical learning model of Sherman and colleagues (2020) suggesting that statistical learning remains effective and detectable with aging through neural representation shaping, but efficient cognitive facilitation and integration over time occur primarily in younger adults.

Furthermore, in Study 3 we provided novel and important evidence on the task-independent, general effectiveness of (adaptive) cognitive training in compensating for and modulating age-related cognitive and neural changes by analysing resting-state neural dynamics. Specifically, we observed that the general age-related shift from large-scale to local neural processing could be modulated by cognitive training, restoring large-scale neural dynamics complexity and information processing capacity. Additionally, we found more task-specific element of compensation related to cognitive flexibility and task-switching in the old-training group supported by local neural processing enhancements in relevant brain areas (Armbruster et al., 2012, 2016). Notably, these training-related changes were prominent only in older adults, whereas younger adults showed less complex and more limited improvements in neural processing capacity. This finding underscores the compensatory account of cognitive training (Lövdén et al., 2012), suggesting that older adults may have greater capacity for improvement, reflected in more complex and widespread neural and cognitive changes.

In conclusion, this thesis explored how age-related changes in cognitive and neural processing can be better understood and leveraged to support older adults' functioning and everyday performance. Our findings showed substantial evidence regarding the changed cognitive and neural profile with (healthy) aging. We (1) reaffirmed the inhibitory deficit hypothesis of aging by detecting increased distractibility, less efficient prepotent response inhibition and cognitive conflict resolution, (2) highlighted the preserved capacity for implicit learning, and (3) demonstrated changes in intrinsic neural processing as a shift from global to local information processing capacity and complexity. As for the investigated modulatory factors of cognitive aging, (1) contextual cueing could be sufficiently applied for supporting visual search performance in older adults, and (2) adaptive cognitive training is suitable for inducing broader and task-independent benefits for compensating cognitive aging by modulating intrinsic neural dynamics and processing efficiency in older adults, however, (3) even though older adults processed task-irrelevant stimuli to a higher extent, they could not encode and use this information efficiently for gaining benefits from them. These insights underscore the potential for targeted interventions to enhance cognitive resilience and promote more independent, adaptable and successful aging.

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