

1 **Individualised COgnitive and Motor learning for the Elderly (ICOME):**

2 **A guiding framework for enhancing motor learning performance**

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24 **Abstract**

25 As we approach a future whereby elder adults aged >65 make up more than 50% of the population in
26 many developed countries, the ability to retain and relearn motor functions is a key outcome of health
27 and wellbeing to maintain an active quality of life. We consider a generic approach for learning and
28 managing motor functions less effective for the wide-ranging differences in motor capacities in the
29 ageing population and hypothesise an increased beneficial influence of using an individualised learning
30 approach instead. In this theory and hypothesis manuscript, we present evidence, provide
31 neurobiologically plausible mechanisms and formulate predictions to support our approach. Firstly, we
32 outline the neurobiology of aging and cover the cognitive control considerations from well-established
33 theoretical motor learning frameworks. Differences in motor sequence learning between elder adults
34 and younger adults are also outlined. An important consideration is that different states of cognitive
35 control can be induced, and we specifically explain why open-monitoring meditation is a suitable
36 approach in the case of elder adults. Combining these, we then present our modelling guidelines for
37 sensorimotor rhythms of synchronisation and desynchronisation of alpha and beta bandwidths during
38 motor sequence learning. Lastly, we formulate specific hypotheses and predictions based on the
39 presented information to support the direction of our Individualised COgnitive and Motor learning for
40 the Elderly (ICOME) research program.

41 Contents

42	1. Introduction	3
43	2. Neurobiology of aging	5
44	2.1. Motor sequence learning and cognitive control	8
45	2.2. The Cognitive framework for Sequential Motor Behavior (C-SMB)	10
46	2.3. Motor sequence learning challenges in the elderly	13
47	2.4. Section conclusion: Cognitive control affecting motor sequence learning in elderly	15
48	3. Targeting cognitive control with meditation in elder adults	17
49	4. Event-related desynchronization/ synchronization for individualisation of cognitive and	
50	motor sequence learning	20
51	4.1. Alpha event-related desynchronization and motor sequence learning in elder adults	21
52	4.2. Beta event-related desynchronization and synchronization for motor sequence learning	
53	in elder adults	22
54	4.3. Modelling guidelines for compensatory mechanisms in elder adults	24
55	5. Conclusion and hypotheses from Individualised COgnitive and Motor learning for the	
56	Elderly (ICOME) framework	26

57

58 1. Introduction

59 Population ageing is a global phenomenon and modelling suggests that by 2050 more than 16% of the
60 world would be made up of elder adults >65 years old (Nations, 2019). In Europe, it is estimated that
61 elder adults will make up >50% of the population by 2070 (AWG), 2017). As life expectancy increases
62 alongside working longevity and retirement age, societies face challenges in terms of age-friendly
63 living, recreational and working environments 2020 (2018). Almost all activities of daily living such
64 as driving to work, typing up documents is made up of well-acquired motor sequences which allow us
65 to navigate, interact with the environment with success and automaticity (Chan et al., 2018).
66 Unfortunately with time, motor sequences that were once an integral part of everyday life slowly start
67 to become more difficult to perform due to changes in the nervous and musculoskeletal system. To
68 learn, retain and relearn motor functions is called motor sequence learning (MSL) and this is an
69 important skill for maintaining a healthy and active life for the elderly.

70 Most health care systems around the world rely on a ‘one-size-fits all’ approach for the
71 implementation of motor learning partly due to limited resources and time (Carmeli, 2017). However,
72 wide-ranging changes in the aging processes leading to differences in cognitive and functional motor
73 capacity in the elderly would suggest that generic programs are less effective at an individual level
74 (Mejia et al., 1998). Firstly, there is currently a lack of research to propose how an individualised
75 approach of motor sequence learning can be implemented based on existing theoretical frameworks.
76 Secondly, the measurements to detect improvement in the elderly are unclear even through there is

77 increased understand of cognitive and motor function changes from modern neuroimaging evidence.
78 This current theory and hypothesis manuscript aims to overcome these gaps by combining current
79 behavioural evidence with established neurocognitive mechanisms to propose a framework. In doing
80 so, we hope that it will help to formulate considerations for future research with elder adults utilising
81 an individualised approach for MSL improvements.

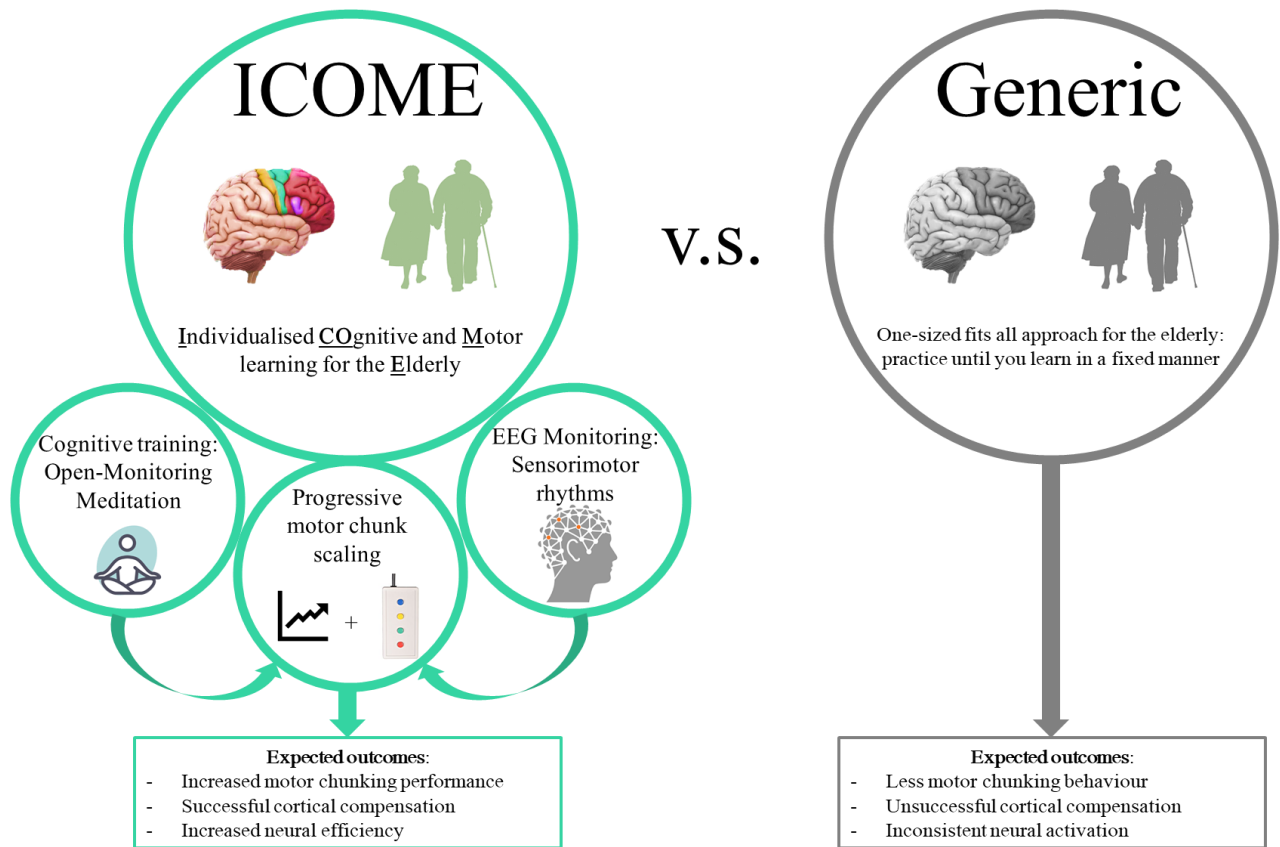
82 To meet our aim, we firstly review the current issues that arise in elder adults from normal
83 aging. Section 2 achieves this by firstly outlining the neurobiology of aging, covering topics such as
84 changes in the cortical structures, cortical compensation and other physical limitations that elder adults
85 face when performing MSL. We then outline the cognitive control considerations in MSL and basis of
86 how sequence acquisition occurs. Very importantly, the formulations of our ideas are drawn from well-
87 established and current theoretical models in MSL, that also clearly outline cognitive control
88 considerations. Current evidence of how elder adults approach MSL differently from younger adults is
89 outlined, alongside how factors such as length of sequences can affect learning performance.

90 Section 3 covers how cognitive control states can affect the manner by which different tasks
91 are performed. One promising approach to target and train cognitive control comes in the form of open-
92 monitoring meditation, which we outline the proposed mechanism of action in elder adults. In Section
93 4, we consider neuro-oscillatory activity that is particularly important for being able to measure changes
94 related to MSL interventions in the elderly. Specifically, we explain sensorimotor rhythms of alpha
95 and beta bandwidths that occur in an event-related manner, giving rise to phases of synchronisation and
96 desynchronisation. We also cover the evidence of change in those bandwidths from MSL and
97 meditation. This then led us to present neurocognitive modelling guidelines when taking into
98 consideration compensatory mechanisms in elder adults and expectations of improvements across
99 behavioural and electrophysiological data during MSL. Lastly in Section 5, we formulate specific
100 hypotheses and predictions based on the presented information to support the direction of the research
101 program – in that individualisation of MSL needs to take into consideration cognitive control and
102 learning factors supported by expected changes in neuro-oscillatory activity. We name this approach:
103 *Individualised COgnitive and Motor learning for the Elderly (ICOME)*, aimed to enhance MSL over
104 generic programs.

105

106

<Insert Figure 1 about here>



107
108

109 **Figure 1.** Generic motor learning programs do not incorporate the needs of the elderly at an
 110 individualised level and result in slow progress and non-optimised outcomes such reduced learning,
 111 unsuccessful compensation and inconsistent neural activation. Our proposed approach to overcome the
 112 limitations of generic programs is called the Individualised COgnitive and Motor learning for the
 113 Elderly (ICOME). The ICOME is a state of the art approach that includes cognitive training in the form
 114 of open-monitoring meditation, scaling of motor chunks give appropriate challenge and monitoring of
 115 cortical changes using EEG. ICOME is expected to increase learning, result in successful cortical
 116 compensation and increase neural efficiency during motor sequence learning.

117

118 **2. Neurobiology of aging**

119 Aging in elder adults leads to compromised neurophysiological functioning, which in turn affect
 120 physical and motor function such decreased movement speed, impaired coordination, reduced postural
 121 and locomotive stability (Seidler et al., 2010). There is a general reduction in overall brain volume of
 122 about 5% with each increasing decade from the age of 40 alongside a decrease in dendritic arbour,
 123 spines and synapses (Peters, 2006). Neurochemical changes also reduce the availability of
 124 neurotransmitters and slow down the rate of conduction and communication (Grafton et al., 1998;
 125 Verwey et al., 2019). Structures such as dorsolateral prefrontal cortex (DLPFC), bilateral posterior

126 parietal cortex, anterior cingulate cortex (ACC) and hippocampus are usually the first to be affected in
127 what is known as the “last-in-first-out” pattern of brain aging (Davis et al., 2009; Raz, 2000). This leads
128 to lower speed and capacity of more global cognitive control functions such as attention, memory,
129 conflict management and inhibitory processes. This means that elder adults will generally have more
130 difficulty to focus and concentrate, to encode or retrieve memory, to resolve and inhibit unwanted
131 responses when performing a goal-related task such as motor sequence learning.

132 More motor-specific cortical structures such as the supplementary motor area (SMA), pre-
133 motor cortex, primary motor cortex (M1), striatum, cerebellum and pons similarly reduce in their
134 volume and conduction capacity (Picard & Strick, 1996; Tanji, 1996). This affects both the cortico-
135 striato-thalamo-cortical loop (cortico-striatal) and the cortico-cerebello-thalamo-cortical loop (cortico-
136 cerebellar) leading to direct MSL and motor adaptation effects respectively (Doyon et al., 2003;
137 Middleton & Strick, 1998). For example, evidence supports that the cerebellum projects cortical output
138 to the M1 and prefrontal cortex, which has increased activation during initial learning of sequential
139 information in both motoric and non-motoric activities such as language (Doyon et al., 2003). The
140 basal ganglia similarly projects to the M1 and prefrontal cortex and are involved in cognitive and limbic
141 functions (Bostan & Strick, 2010). In turn, the striatum together with the caudate-DLPFC, forms an
142 important frontal-striatal circuit to support the formation of associations between repeated presentations
143 of elements that are necessary for MSL (Jueptner et al., 1997). During learning motor cortical output
144 maps from M1 also become progressively larger during early acquisition, and when movements become
145 automated and knowledge is acquired, return back to baseline activation levels (Pascual-Leone et al.,
146 1994). Degradations of cortical and sub-cortical areas therefore directly reduce perceptual and
147 cognitive processing capacity that supports motor learning in elder adults, resulting in slower responses.
148 In more severe disease cases such as Parkinson’s, motor cognition – which is the ability to understand
149 and predict movement outcomes, is directly compromised by the degradation of the cerebellum and
150 basal ganglia, making planning, learning and execution of acquired motor programs problematic
151 (Fuentes & Bastian, 2007).

152 The nervous system also undergoes changes at the peripheral level with aging.
153 Mechanoreceptors that relate to movement, tension, pressure, and proprioceptors which inform of the
154 sense of position of the body, reduce in their integrity and capacity to integrate peripheral feedback
155 signals to the central nervous system. This kind of degeneration exists in the form of less free nerve
156 endings and reduced myelination of sensory neurons. Less feedback from peripheral processes reaching
157 the central nervous system leads to reduced bodily awareness during motor task performance and
158 learning (Hansell & Mechanic, 1991; Seidler et al., 2002; Seidler et al., 2010). In addition, elder adults
159 have physical limitations in using their extremities such as fingers to perform motor learning quickly,
160 but could learn just as well as younger adults with extended practice (Barnhoorn et al., 2019). This
161 further supports that with sufficient practice, internalised representations of motor sequences between

162 elder and younger adults do not differ significantly (Barnhoorn et al., 2016). Questions such as the
163 optimal practice quantity or the kind of practice to optimise learning linger with no available evidence
164 from the elderly population.

165 Despite all these reductions in the central and peripheral nervous system, many elder adults are
166 mobile, maintain good physical function capacity and can ambulate quite freely. From this point forth,
167 the elderly population of interest in this manuscript are considered *apparently healthy*, and we will not
168 focus on clinical populations. In general, elder adults are known to be slower in many motor-related
169 behavioural outcomes compared to younger adults although they maintain similar accuracy levels
170 (Mattay et al., 2002). This is because most elder adults utilise a strategy to prioritise movement
171 accuracy at the cost of movement speed (Seidler-Dobrin et al., 1998). In addition, because of poorer
172 cognitive processing capabilities and reduced input from sensory structures, elder adults have been
173 shown to overcompensate in order to adapt and support motor performance through cortical over-
174 activation (Mattay et al., 2002). This is also linked with the “last-in-first-out” pattern of brain aging,
175 whereby age-related white matter integrity reductions decrease in an anterior-to-posterior gradient for
176 prefrontal regions, tracts (including corpus collosum) and uncinate fasciculus (Cabeza & Dennis, 2013).
177 Compensation in the cortex occurs in two main mechanisms: 1) increased hyperactivity in intact cortical
178 areas which means that there is an increase in the neural supply and activation (i.e. increases in BOLD
179 response, event-related oscillatory amplitudes etc.); 2) increase activity and additional recruitment of
180 remaining healthy cortical areas as (i.e. bilateral activation, increased functional connectivity) by the
181 aging brain (Cabeza & Dennis, 2013; King et al., 2013). The neuroplastic reorganization and
182 redistribution of cortical circuitry to other relatively healthy and intact areas are especially important
183 mechanisms that support successful MSL in elder adults (Peters, 2006). For example, in younger adults,
184 hippocampal activity decreases alongside striatal activity increases as a function of MSL (Albouy et al.,
185 2008), whereas in elder adults, it has been show that activity in both hippocampus and striatum increases
186 during similar MSL performance (King et al., 2013; Kubica et al., 2019).

187 Heuninckx et al. (2008) also found that elder adults had increased frontal cortical activation,
188 areas which are associated with attention and cognitive control processes compared to younger adults
189 when performing motor actions similar to activities of daily living (Cabeza, 2001). This indicates that
190 motor control for usual actions and when learning novel ones, require more cognitive resource
191 activation in the form of increased cognitive control to support successful performance in elder adults
192 is required compared to younger adults. It should be noted that increased frontal activation does not
193 mean that performance is poorer for elder adults. For example, high-performing elder adults have been
194 shown to counteracted age-related neural decline through a plastic reorganization of prefrontal cortex
195 networks, showcasing increased bilateral activation patterns when performing memory tasks (Cabeza
196 et al., 2002). This is what is referred to as the Hemispheric Asymmetry Reduction in Older Adults
197 (HAROLD) pattern which is evident during performance tasks that require attention and memory

198 (Cabeza et al., 1997). In comparison, lower-performing elder adults and young adults only showcased
199 unilateral activation dominant in the right prefrontal cortex.

200 Although the aging process is largely modulated by cellular processes (Raz, 2000), it is
201 suggested that environmental influences can alter some of these processes to improve basic neuronal
202 and cognitive functioning in a manner that maintains high performance (Arking, 1998). This provides
203 a premise that by extension external activities and practice conditions may improve and enhance MSL
204 performance. This is very promising for apparently healthy elder adults aiming to maintain functional
205 capacity in later years. In sum, it appears that aging affects cognitive control, motor control for usual
206 actions, and when learning novel motor sequences. The current evidence supports that with cortical
207 deterioration, more cognitive resource activation and/or greater recruitment of cortical areas (i.e.
208 compensation) is evident to support successful performance in elder adults compared to younger adults.
209 Compensation also has implications if we want to tailor an individualised motor learning program for
210 elder adults to increase learning outcomes compared to generic programs. Cognitive control must
211 therefore also be considered as part of a wholistic approach for learning improvements. In the next
212 section, we focus on MSL and cognitive control considerations for elder adults, and further in Section
213 4.3., we expand on how compensatory mechanisms inform of our modelling approaches.

214 **2.1. Motor sequence learning and cognitive control**

215 Whilst there are different MSL paradigms (e.g. the serial reaction timed task), we aimed not detail them
216 all but to focus on the Discrete Sequence Production task (DSP) task (Verwey, 1999, 2001) as the main
217 paradigm. The main reason is because the DPS task has well-developed theoretical frameworks
218 supporting it, it is scalable, and its application has broad coverage to explain majority of sequential
219 learning behaviour. The DSP task is typically performed on a computer where learners use a keyboard
220 to practice two short key pressing sequences of between 3–7 stimuli separated with a clear break
221 (Verwey et al., 2019). A series of placeholders (in the form of small squares) are displayed on a monitor,
222 and each of the placeholders correspond to one of the keys of the keyboard in a spatially compatible
223 manner (see Abrahamse, Ruitenberg, de Kleine, & Verwey, 2013). When a placeholder lights up,
224 learners rapidly press the spatially compatible key and the next stimulus is displayed with no time lag
225 from the previous response. The DSP task has two distinctive features, firstly it starts with a practice
226 phase of between 500–1000 repetitions per sequence whereby learners react to two series of key-
227 specific stimuli. With practice, the DSP task turns into a two-choice reaction time task and each
228 response consists of a familiar keying sequence to develop the building blocks of more complex motor
229 movements (Arnold et al., 2017; Verwey et al., 2019) with an ability to scale for different skill levels.
230 Being able to scale is important for elder adults, as it means that the DSP can be individualised to meet
231 adequate challenge, and therefore potentially increase learning improvements. We further unpack
232 specifics in Section 2.4.

233 The second feature of the DSP is that sequences are usually counterbalanced for the positions
234 of sequential positions usually by performing a rightward shift of keys. This allows for specific effects
235 due to sequential positioning to be ruled out, as each of the fingers contributes equally to the reaction
236 times (RTs) (Abrahamse et al., 2013). Counterbalancing ensures that same sequences can be familiar
237 and unfamiliar not because of control-order but due to underlying cognitive control processes.
238 Cognitive control in MSL operates as a set of higher-order cortical operations, that integrate perceptual,
239 central and motor processes for successful motor learning (Gratton et al., 2017; Verwey et al., 2015).
240 These processes regulate attention (i.e. focus and concentration), working and long-term memory (i.e.
241 building of sequence representations), and other executive functions (i.e. response selection, conflict
242 resolution, and task representation) in a manner that increases learning performance with practice
243 (Daltrozzo & Conway, 2014; Keele et al., 2003; Slagter et al., 2011). We expect that these functions
244 are somewhat compromised in elder adults due to the deterioration of the cortical structures associated
245 with their functions (e.g. prefrontal cortex and top-down attention; hippocampus and memory encoding
246 etc.). Despite this, elder adults still follow incremental phases in their learning of motor sequences. For
247 example, the cognitive processing for early learning in the DSP typically occurs at a stimulus-level
248 which focuses on perceptual processes to support stimulus identification, followed by intermediate
249 preparations for appropriate response selection. This is known as a stimulus-to-response mapping (S-
250 R), and draws upon acquiring specific cues that trigger corresponding motor responses (Tubau et al.,
251 2007). The second type of learning known as stimulus-to-stimulus mapping (S-S) also relies on a large
252 amount of perceptual integration and posits that learning effects are based on creating associations
253 between stimulus features independent from response features. This type of learning does not transfer
254 well when stimuli features are changed, for example, when there is a right-ward shift of spatial
255 positioning or change in colours (Abrahamse et al., 2008). In both stimulus-based associations,
256 cognitive control is reinforced such that attention prioritizes the processing of stimulus features. As
257 learning advances, responses codes start to gain importance for the development of internal
258 representations of the sequence. In this case, response-to-response mapping (R-R) which refers to the
259 formation of response features independent from stimulus level features starts to dominate (Koch &
260 Hoffmann, 2000). This denotes that the cognitive control of MSL has shifted from external control
261 based on perceptual information processing towards an internal control, alongside the development of
262 an internalised and robust representation and/or increasing stable motor program (Hoffmann & Koch,
263 1997; Koch & Hoffmann, 2000).

264 In the DSP task, greater response-mapping leads to an increase in the development of smaller
265 spatial representations of the motor sequence also known as *motor chunks* (Abrahamse et al., 2013;
266 Miller et al., 1960; Verwey & Abrahamse, 2012; Verwey & Dronkert, 1996). Motor chunks are
267 described as representations of successive movements that can be selected, initiated and executed as a
268 single response (Verwey, 1999). In the DSP task, motor chunks are usually characterized by a relatively

269 slow first key press (due to a need to identify and assemble the motor chunk) followed by a series of
270 key presses that are executed quickly and smoothly due to an established internalised representation of
271 the next few upcoming responses (Verwey & Abrahamse, 2012; Verwey et al., 2015). However, motor
272 chunks are somewhat limited by working memory constraints and sequences that contain >5 key presses
273 typically have a concatenation point that results in a relatively slower key press around the 4th key press,
274 followed by faster key presses after that point due to the execution of another secondary motor chunk
275 (Abrahamse et al., 2013; Verwey, 2001; Verwey & Abrahamse, 2012). In the next section, we unpack
276 the Cognitive framework for Sequential Motor Behavior (C-SMB) which explains how learning modes
277 and strategies arise when elder adult learners perform the DSP task.

278 **2.2. The Cognitive framework for Sequential Motor Behavior (C-SMB)**

279 The formation of S-R bindings that build into R-R associations and into motor chunks is due to MSL
280 being a goal-directed task, aimed towards performance efficiency in both speed and accuracy
281 (Danielmeier et al., 2011; Forstmann et al., 2011). In pursue of efficiency, different learning strategies
282 arise to achieve expertise, supported by distinct contributions from the various cortical structures and
283 neural processing (Verwey et al., 2019). In the past, learning strategies were understood from
284 behavioural results, but recent work has suggested that better inferences can be made when cortical
285 activation supporting the behavioural results are modelled more comprehensively using modern
286 computation (Abrahamse et al., 2016). In doing so, we can formulate clearer predictions when just
287 observing cortical activation patterns and vice versa, to ascertain that behavioural results and learning
288 strategies are supported by expected cortical areas (Verwey et al., 2019). To guide us on these
289 expectations and cognitive contributions, we draw on the *Cognitive framework for Sequential Motor*
290 *Behavior* (C-SMB) (Verwey et al., 2015).

291 The Cognitive framework for Sequential Motor Behavior (C-SMB) is an extension of the Dual
292 Processor Model (DPM), which originally showed that a cognitive and motor processor race to execute
293 discrete motor sequences until performance is smooth and efficient (Abrahamse et al., 2013; Verwey et
294 al., 2015). In the C-SMB, the cognitive processor is now understood as a central processor that acts as
295 an intermediary between the perceptual and motor processors. The inclusion of perceptual processor is
296 new and it is responsible for modality-specific extraction of visual, auditory, or proprioceptive features,
297 such that the central processor acts in a versatile manner to process both familiar and unfamiliar
298 movements. The inclusion of the perceptual processor means that the C-SMB implicitly also considers
299 the degradations at the peripheral level in elder adults. Further in Section 3., we expand on why the
300 link between perceptual and the central processor is of an importance in elder adults and that it may be
301 possible to strengthen this connection through cognitive training, and in turn improve the processing of
302 sequential information to increase learning outcomes. Returning to the central processor, it is assumed
303 to utilize short-term memory and operates in a more generalised manner to contextualize current motor
304 requirements from previously learnt motor programs for feature extraction. The motor processor then

305 takes over and becomes dominant once it has integrated the new information and gained a level of
306 automaticity with current motor sequence requirements for high performance.

307 During early practice, the increase in S-R bindings are facilitated by the central processor that
308 ‘reacts’ to each externally presented stimulus with an associated response that is competing against the
309 motor processor to execute. A motor buffer (assumed to be part of working memory) bridges between
310 the central and motor processor and stores a limited number of responses before executing them. It has
311 been shown that the motor buffer can prepare up to four different responses and execute them as one
312 single response as if it were a simple RT task (Verwey & Dronkert, 1996). At this stage, learners are
313 utilizing strategy in which what Verwey and Abrahamse (2012) refers to as *reaction mode* and the focus
314 is on responding to the stimuli in an externally guided manner. The stimulus is used to signal a specific
315 response in an automated way, but does not allow for further elaboration in the context of the sequence
316 (Tubau et al., 2007) and sequence learning is carried out in a reflex-like manner (Hommel, 2000). In
317 this case, we can expect the central processor to dominate with limited utilisation of the motor processor.

318 The next strategy in motor sequence learning is characterised by an *associative mode* whereby
319 the cognitive processor starts to elaborate beyond simple S-R bindings and focus on developing
320 associations in successively used representations at various processing levels. Although at this stage
321 these associations are weak, they are the beginnings of internalised plans that develop as learning ensues
322 (Elsner & Hommel, 2001). Cognitive control is utilizing the information from errors to make future
323 responses more efficient by prioritising the encoding of several responses into a series so that they could
324 be executed in a familiar order. The central processor is still assumed to be dominant compared to the
325 motor processor. When the internalised representation becomes sufficiently strong, there is a reduced
326 reliance of S-R bindings and more towards R-R bindings at an automated motoric level. This is known
327 as the *chunking mode* and allows for several motor chunks to be combined for co-articulation and
328 responding. The internalised representation of the sequence is strong and therefore representations can
329 minimize the involvement of the cognitive process by directly loading motor chunks into the motor
330 buffer. This is followed by the motor processor directly executing the motor chunks for fast and
331 accurate responding. It is important to note that motor chunks are stable and effector-specific, which
332 means that if there is a disruption to the prepared chunk or by changing the modality in which the
333 sequence is executed (e.g. hand or keyboard), physical performance can be negatively affected although
334 abstract representations are still intact (Grafton et al., 1998). This suggests that cognitive control does
335 not fall back directly to the central or perceptual processor but rely on drawing upon *central-symbolic*
336 representations that align with the learning task. The C-SMB refers to the central-symbolic as other
337 associative modality representations such as successive spatial and/or verbal ones that are used to bridge
338 learning performance. Of note is that the different cognitive modes/ systems are working in parallel to
339 determine the ‘best’ course of action to optimise learning goals.

340 One of the distinct features in the C-SMB is the recognition of cognitive control contributions
341 from reaction to chunking modes for sequence execution. Cognitive control operates in a manner that
342 is described by Koechlin and colleagues as a cascading hierarchical gradient for information processing
343 (Koechlin et al., 2003; Koechlin & Summerfield, 2007). In this gradient, posterior regions of the pre-
344 frontal cortex (PFC) support goal-directed responses based on immediate sensory context (i.e.
345 perceptual processor). In reaction mode, we expect cognitive control to processing proximal
346 information from one stimulus to one response and then to the next stimulus relying on sensorimotor
347 control dominated by premotor activation. In this situation, the most anterior areas of the frontal lobes,
348 the frontopolar cortex (FPC) are most readily contributing to maintain enhanced cognitive control in
349 support of learning (Koechlin & Hyafil, 2007). This was supported by fMRI imaging during
350 performance of unfamiliar sequences, whereby bilateral DLPFC and anterior parts of the striatum work
351 to support the motor buffer in a cortico-subcortical loop (Verwey et al., 2019). The interpretation is
352 that DLPFC activation supports cognitive control enhancement for increased attention to react to the
353 spatial aspects during early motor sequence learning (Dayan & Cohen, 2011; Verwey et al., 2019).

354 When the cognitive system shifts towards central-symbolic representations, it was shown that
355 the inferior parietal cortex showcases increased activation together with a shift of sensorimotor cortex
356 towards a more dorsal locus. Taken together with an increase in cerebral blood flow in the cingulate
357 motor area, it supports that sequences have been encoded at an abstract level and that the task-relevant
358 effector system is activated (Grafton et al., 1998). When learning shifts further on towards associative
359 and then to chunking mode, cognitive control becomes more flexible and operate in a relatively reduced
360 state compared to at the start of learning. It should be noted that frontal cortices are still tonically active
361 to attend to targets and maintain current goals albeit in a less active manner (Koechlin & Hyafil, 2007).

362 Reductions of PFC activations in the frontal parts of the brain allow for a more striatum-
363 dependent learning system that is not so reliant on the connectivity between PFC and ACC for control
364 of actions (Nemeth, Janacek, Polner, et al., 2013). The striatum-dependent learning system is more
365 aligned with automated sequential learning systems that are the basis for increases in other measures
366 such as memory and chunking. Memory (both motor buffer and long-term memory) plays an
367 increasingly important role in encoding response features with less dependence on stimulus features
368 and therefore greater activation in the hippocampus (Albouy et al., 2008) and entrainment of the other
369 cortical structures from the hippocampus such as the basal ganglia (Jafarpour et al., 2017). Evidence
370 suggest that hippocampal involvement is indicative of increased encoding of the motor sequence into
371 internalized central-symbolic representations with communication with the basal ganglia to support the
372 development of motor chunks (Dayan & Cohen, 2011; Verwey et al., 2019). As learners start to develop
373 sequence familiarity and when motor chunking is increasingly being utilised as the main strategy, there
374 is a decrease of the premotor-associative striatum-cerebellar network and stabilisation in the
375 connectivity within the M1-sensorimotor striatum-cerebellar network, with an expect shift of increased

376 neural activation to the preSMA, SMA, M1 and basal ganglia (Dayan & Cohen, 2011; King et al., 2013;
 377 Verwey et al., 2002). In sum, we can expect an anterior to posterior shift of cortical activation as
 378 learning strategies and expertise develops from initial reaction to chunking modes. There should also
 379 be a reduction of relative cortical activation in a gradient fashion from initial learning as a function of
 380 increasing expertise. In the next section, we outline how the learning process is affected in the elderly.

381 **2.3. Motor sequence learning challenges in the elderly**

382 There are several differences in MSL performance in elder adults compared to younger adults. On the
 383 surface, it appears that absolute RTs are longer in elder adults compared to younger adults, but this
 384 relationship is far from providing the complete picture (Barnhoorn et al., 2016). The initial fast MSL
 385 phase appears to be intact whereby elder adults have demonstrated significant improvements as a
 386 function of practice, suggesting that elder adults can still utilize a reaction mode for correct responding
 387 (King et al., 2013; Nemeth & Janacsek, 2011; Nemeth, Janacsek, & Fiser, 2013). This is despite known
 388 physical factors that affect RTs such as stiff fingers, handedness and wrist rotations from previous work
 389 (Barnhoorn et al., 2019). But more importantly, learning conditions that induce conditions of increased
 390 complexity in the motor sequence are also responsible for deficits in learning rate and magnitude
 391 (Curran, 1997). For example, when explicit instructions were given to elder adults to learn a sequence
 392 based on an abstract rule, the complexity of the task became too difficult for elder adults and instead
 393 impeded learning (Howard & Howard, 2001). It is likely that the upper end of cognitive capacity for
 394 elder adults is lower than younger adults due to the ageing process, and that additional instructions
 395 required cognitive resources beyond the limit of working memory processes which led to reduced
 396 learning (Pinotsis et al., 2018). It is also a premise that more can be done to in the cognitive control
 397 domain to improve and optimise learning conditions in the direction of deriving appropriate challenge.

398 Sequence representations in the form of motor chunking behaviour in younger adults also on
 399 the surface seem to be less developed in elder adults due to declines in visuospatial working memory
 400 (Bo et al., 2009; Kruger et al., 2017). The tendency is for elder adults tend to learn the general task of
 401 responding by relying on external cues, and that younger adults are more readily able to extract
 402 regularities in a sequence to develop their internalised representations (Verwey, 2010). For example,
 403 when Barnhoorn et al. (2016) utilized two six-element sequences to perform a classical key-pressing
 404 DSP and a flexion-extension version using a lever performed 144 times, it was found that elder adults
 405 were able to transfer from flexion extension to key-press but not vice-versa. In absolute terms, general
 406 RT improvement, processing speed and knowledge of explicit knowledge was less than younger adults.
 407 However, it was found that larger visuospatial working memory capacity was associated with quicker
 408 sequence learning when performing key-press movements even in elder adults. This meant that
 409 sequence representation in elder adults are similar to that of younger adults, and that flexible application
 410 of sequential knowledge is still preserved in elder adults (Barnhoorn et al., 2016).

411 In another instance of understanding motor chunking behaviour, Barnhoorn et al. (2019) found
412 that the once thought of reduced chunking in elder adults can become more normalized under certain
413 conditions. Their work showed that by using shorter sequences of 3- and 6-elements with extended
414 practice of 432 times in the DSP, age group and interaction effects were not significant although
415 absolute RT differences were still evident. More importantly, they found that explicit sequence
416 knowledge was correlated with chunking behaviour, suggesting that elder adults execute sequences
417 based not just on pure motor representations. This finding links together with the C-SMB framework
418 that representations underlying motor skill in elder might be shared with more general visuospatial
419 central-symbolic representations of similar skilled sequence performances to bridge their learning. In
420 other words, elder adults still retain the ability to utilise cognitive control to draw on previous motor
421 experiences (through long-term memory recall) to attend and learn new motor sequences with the
422 central-symbolic working in parallel with other systems. The authors concluded that with extended
423 practice, there were no differences in motor chunking behaviour between younger and elder adults.
424 These recent evidences are promising as they indicate that there are certain conditions that facilitate
425 more effective motor sequence learning in elder adults such that the performance is relatively similar
426 to younger adults (still slower) despite changes in cortical matter and reduction in cognitive abilities.

427 The current premise is that with enough practice similar learning outcomes will occur in
428 apparently healthy elder adults although there is currently a gap in research that does not address if this
429 learning process can be optimized without a need for extended practice. Specifically, we want to
430 consider two ideas that are promising and can be applied to increased motor development in elder adults.
431 Firstly, the work of Barnhoorn et al. (2019) support that short 3- and up to 6-item motor chunks are
432 well-tolerated by elder adults for learning. This points towards the use of a part-practice approach
433 compared to whole practice techniques (Fontana et al., 2009; Schmidt & Wrisberg, 2008). For example,
434 if the goal is for elder adults to learn the complete sequence of 6-items then practice could be scheduled
435 in a way that builds from 3-, 4-, 5-, to the complete 6-item in a progressive manner. In physical activities
436 and sports training, this kind of approach has been shown to be effective with sequential tasks like the
437 DSP whereby a high cognitive load is required but consists of serial elements of increased complexity
438 albeit low in organization (Fontana et al., 2009; Naylor & Briggs, 1963). We propose that by using
439 what is known as a part-practice approach that accounts for the appropriate amount of challenge,
440 suitable scaling can maximise learning outcomes. This notion also falls in line with earlier evidence
441 presented with regards to cortical compensation in elder adults (Cabeza & Dennis, 2013), and that
442 appropriate challenge should not overtax available cognitive control and memory resources. An
443 overtaxed cognitive system was shown to be detrimental for MSL and inhibit the building of sequence
444 representation and use of motor chunks (Howard & Howard, 2001; Pinotsis et al., 2018).

445 Secondly, the appropriate practice amount is also of question. Earlier, we presented that with
446 144 times practice of a sequence, elder adults were not able to derive as much learning and only when

447 practice was extended to 432 times that motor chunks were developed (Barnhoorn et al., 2019). The
448 risk here is that boredom and reduced attentional focus might arise from over practice, working against
449 the compromised upper limit of cognitive abilities and may bring about reduced learning in the elderly.
450 Indeed, in some cases elder adults have shown poorer MSL consolidation effects that maybe linked to
451 inappropriate practice quantity (Brown et al., 2009; King et al., 2013). We consider that practice
452 quantity and quality are both of importance (Williamon & Valentine, 2000) and should be an important
453 factor to optimise MSL in elder adults.

454 **2.4. Section conclusion: Cognitive control affecting motor sequence learning in elderly**

455 Cognitive control is linked with the operation of cortical networks that support MSL, and recently
456 shown that induced control states may modulate the use of reaction mode or facilitate the development
457 of central-symbolic and the use of chunking modes (Chan et al., 2017). The proposed mechanism
458 suggested by Amer and colleagues (Amer et al., 2016; Amer & Hasher, 2014) posit that cognitive
459 control is contextually driven and works dynamically in a double-edged manner. Increased cognitive
460 control states appears to benefit tasks that require focused attention to suppress distraction while
461 increasing the speed of processing (Lustig et al., 2009) and comprehension for success (Mund et al.,
462 2012). In contrast, weakened cognitive control states benefit tasks that require more diffused attention
463 to incorporate a variety of stimuli for creative task solving, learning of statistical regularities (Schwab
464 et al., 2016) and retrieval of memory (Campbell et al., 2012). Further evidence for this was shown
465 when Biss et al. (2013) compared the performance of a task that required remembering a list of words
466 between a group of older and younger adults. Unknown to the participants during the performance of
467 a one-back task, half of the words in the list were presented as distractors. The results demonstrated
468 that elder adults rarely forgot words that were presented as distractors while younger adults forgot words
469 in both the original list and as distractors. It suggests that elder adults were performing the task with
470 weakened cognitive control which allowed them to use the so-called irrelevant distractions as a
471 rehearsal episode to solve the task more creatively. Younger adults, in contrast, performed more
472 accurately on the one-back task by prioritising current tasks performance through increased attentional
473 focus and suppression of distractors, which points towards performance with increased cognitive
474 control (Amer et al., 2016; Biss et al., 2013). These control effects support that cognitive control is
475 double-edged that it may influence how elder adults may frame the competition of goal-relevant
476 information (Friedman & Miyake, 2004) and subsequently affect MSL performance.

477 Earlier we explained in the C-SMB, different execution modes ‘compete’ to facilitate different
478 way to execute sequences during MSL, which posits that this competition is linked to the double-edged
479 nature of cognitive control. This can be explained by what Hommel (2015) refers to as an interplay
480 between persistence and flexibility in the Metacontrol State Model. Greater persistence is applied by
481 increasing cognitive control and prioritising the processing of local competition against a goal (e.g. to

482 maintain speed). Decision-making becomes more selective to reduce and/or inhibit in compatible
483 information and actions that does not serve the goal during sequence acquisition are reduced. Local
484 competition between targets in the DSP therefore prioritises reinforcing S-R binding and reaction mode
485 (Tubau, Hommel, et al., 2007; Verwey et al., 2015). In contrast, when there is a reduced need for the
486 maintenance of task goal performance, then cognitive control allows for increased flexibility to other
487 possible solutions. When one reduces the impact of the goal, there is increased flow of information
488 from seemingly irrelevant or inconsistent stimuli which may provide alternative solutions. Weakened
489 cognitive control states can therefore tolerate the selection of multiple targets and learning starts to
490 utilise an associative mode. Sequence automatisations ensue with increases in the development of motor
491 chunks in the DSP and the building of an internalised plan (Abrahamse et al., 2013; Franco &
492 Destrebecqz, 2012; Verwey et al., 2015).

493 It should be highlighted that weakened cognitive control does not mean that attention less
494 focused or distracted on the stimuli presented in comparison to increased control states. The attentional
495 function during MSL perceives possible targets that might require response towards. The difference
496 lies in that weakened cognitive control facilitates attention to operate in a wider ‘aperture’ to tolerate
497 multiple targets (Broadbent, 1958; Eriksen & St James, 1986) and explore possible relational elements
498 for alternative ways to respond and eventually acquire a plan for efficiency. Nemeth, Janacek, Polner,
499 et al. (2013) demonstrated this when using hypnosis prior to and during MSL to induce states of
500 weakened cognitive control which subsequently boosted learning performance. The authors outline
501 that reductions of PFC activations in the frontal parts of the brain allowed for a more striatum-dependent
502 learning system to be active and rely less on the connectivity between PFC and ACC for the control of
503 actions (Nemeth, Janacek, Polner, et al., 2013). The striatum-dependent learning system is aligned
504 with procedural-based systems in a more automated fashion and therefore may increase performances
505 in memory and motor chunking. It should also be noted that the cognitive control states are relatively
506 inert, and have lasting effects on later control policies, even after a new operating state has been
507 implemented from a different task evidenced from task-switching paradigms (Allport et al., 1994;
508 Kiesel et al., 2010). We consider that this as a plausible mechanism that could induce states of
509 weakened cognitive control for the elderly to enhance their MSL performance.

510 In the previous section, we also proposed the possibility of what is considered a part-practice
511 approach for MSL. We would like to coin the term *progressive-chunk* to describe this as training
512 approach for the MSL task like the DSP which we think is suitable for elder adults. This premise is
513 also grounded in cognitive control such that the implementation of MSL appropriately challenges the
514 cognitive system of elder adults. If chunks are too small and over practice is provided, then elder adults
515 maybe underutilizing cognitive control to learn, resulting in boredom and reduced engagement of
516 learning. Consequently, if chunks are too long and complex, then elder adults may be overtaxing
517 cognitive control with cortical activation that is beyond available resources and functional connectivity,

518 resulting in also reduced learning performance. Currently, there are no known evidence that outline
519 what is a suitable evidence-based approach to provide the right amount of challenge for elder adults
520 performing MSL for increased performance compared to generic programs. We consider this gap could
521 be addressed with cognitive control considerations measured and analysed alongside behavioural
522 changes and propose our predictions in Section 4.3.

523 To conclude this section, we firstly highlighted the physiological limitations in elder adults
524 stemming from the ageing process in both the central and peripheral nervous system. We covered how
525 specific motor learning cortical areas affect MSL and how learning arises through a review of the C-
526 SMB. The challenges elder adults faced during MSL and how cognitive control can be orientated in an
527 increased or weakened manner that affects the processing of relevant information were also highlighted.
528 The key idea is that cognitive control states are inert but can also be influenced by other activities. If
529 the goal is to optimise MSL in elder adults, then we must consider ways in which optimal cognitive
530 control states could be induced to support learning performance. The next section will review how
531 meditation can bias cognitive control states that may benefit MSL in elder adults.

532 **3. Targeting cognitive control with meditation in elder adults**

533 Meditation is an ancient mental practice that can be traced back to Vedic philosophy as far back as
534 1500BCE (Everly & Lating, 2002). Although there are a wide variety of meditation practices, a large
535 majority of them are comprise of internalized and self-regulated mental practices used to cultivate
536 positive qualities in the mind (Lee et al., 2018). As a result of the practice, an enhanced insight into the
537 mind and body together alongside cognitive benefits are often reported (Vieten et al., 2018). The
538 purpose of this section is to provide an outline of the effects of using meditation as an adjunct cognitive
539 practise, to enhance MSL with cognitive control considerations. A large majority of the meditation
540 studies report well-established benefits in both affective and cognitive functions (Chiesa et al., 2011;
541 Davidson et al., 2003; Slagter et al., 2011; Tang et al., 2015), which we consider especially relevant to
542 our approach with cognitive control considerations. However, there are some studies which did not
543 show that meditation training could result in cognitive benefits. For example, Van der Lubbe et al.
544 (2018) showed that although self-reported mindfulness increased following 6-weeks of mindfulness
545 training, attentional performance during a Go/NoGo task alongside event-related potentials and alpha
546 power did not change. Although the study suffered from a design perspective of not using a gold-
547 standard approach of an active-control group (Davidson & Kaszniak, 2015), it does show that cognitive
548 benefit effects can vary in different circumstances.

549 We want to highlight several neurophysiological phenomena that is promising and may be of
550 benefit to the cortical reorganization of elder adults and contribute to cognitive function maintenance.
551 Firstly, several studies have shown that regular meditation practice appears to upregulate neuroplasticity
552 and reduce age-related brain degeneration (Lardone et al., 2018; Luders, 2014; Newberg et al., 2014).

553 Specifically, Luders et al. (2011) found that brain connectivity and white matter integrity in both cortical
 554 and sub-cortical areas were modulated by the amount of meditation practice and age. In other words,
 555 older meditators with greatest number of hours of practice showed the least amount of age-related
 556 decline compared to age-matched controls. Since we expect a reduction of asymmetry in terms of
 557 cortical activation for elder adults, structures such as the corpus callosum are important that facilitate
 558 interhemispheric communication. In other works, meditation practice has also been found to be
 559 associated with thicker callosal regions and enhanced integrity, which might indicate greater
 560 connectivity, and increased hemispheric integration during cerebral processes involving prefrontal
 561 regions (Holzel et al., 2011; Luders et al., 2012). It has been further shown that such changes in callosal
 562 regions has been shown to be evident from as little as 11 hours of meditation training in naïve
 563 individuals (Tang et al., 2010). The evidence in functional neuroimaging appears to support that
 564 meditation can induce some level of neuroprotection against aging effects in elder adults (Gard et al.,
 565 2014; Lazar et al., 2005), which in turn may enhance performances that require attention, memory (Jha
 566 et al., 2007; Lutz et al., 2015) and cognitive control networks (Lutz et al., 2008; Tang et al., 2015; Tang
 567 et al., 2007).

568 Meditation practices can be broadly divided into two categories: *focused-attention* (or
 569 concentrative style) meditation (FAM) and *open-monitoring* (or mindful approach) meditation (OMM),
 570 depending on how the attentional processes are directed (Cahn & Polich, 2006; Hommel & Colzato,
 571 2017). At the core of both styles is the training of attention, which is believed to exert effects on other
 572 core psychological processes such as emotional and cognitive flexibility in a bidirectional manner
 573 (Malinowski, 2013). The goal in the practice of FAM is to mentally focus attention on specific mental
 574 or sensory activity such as the breath or awareness of body parts (Lutz et al., 2015; Slagter et al., 2011).
 575 It is thought that FAM trains attentional control by performing cognitive control operations in a cyclical
 576 manner that monitors and recognising distractions; facilitates disengagement from distraction; and
 577 shifts attentional back to the original object focus as given in the instructions (Gallant, 2016;
 578 Malinowski, 2013; Tang et al., 2015). This cyclical practice of attention is considered to entrain
 579 cognitive control networks related to alerting, orienting, inhibition of irrelevant information and thought
 580 to underly the neuroanatomical changes from practice (Hasenkamp & Barsalou, 2012; Malinowski,
 581 2013). As a result, FAM practice is believed to reinforce and increase cognitive control.

582 If guided by C-SMB if cognitive control is reinforced, then we would expect the use of reaction
 583 mode enhancing S-R bindings with less opportunity to develop motor chunks. We consider that this
 584 mechanistic action of FAM may therefore not be the most beneficial training for elder adults who
 585 already have an increased cognitive control due to their neurophysiological deteriorations. However,
 586 let us briefly review some of the evidence to support why we would not utilise FAM for elder adults.
 587 Firstly, when a single-session of FAM immediately preceded MSL, greater reduction in response times
 588 and improvement in general learning performances compared to a control group was due to increased

589 reaction mode utilization with no differences in sequence-specific effects (akin to motor chunking)
590 (Chan et al., 2018). Follow up work showed that overall cognitive control indicated by the N2 event-
591 related potential, was enhanced following 21-days of FAM training during MSL compared to learners
592 that did not perform FAM training (Chan et al., 2020). Both instances support that a greater level of
593 cognitive control can be expected from FAM practice and that this was the main mechanism for motor
594 sequence learning enhancements. In the C-SMB, it would signify a greater reliance of the central
595 processor to develop a learning strategy for MSL, which may not be the most optimised approach for
596 most elder adults that exhibit increases in cortical activation.

597 OMM in contrast to FAM, is promising for application as cognitive enhancement for elder
598 adults performing MSL although yet to be investigated at this stage. The fundamental feature that is
599 different from FAM is that training of attention is characterized by being aware of general sensory
600 processes in a “nonreactive” and “mindful” manner with a goal to apply nonjudgmental thinking
601 (Lardone et al., 2018). OMM is also typically characterised by reduced instructions and attention is
602 tonically active but not overtly activated, which may facilitate an integration of information from
603 different sources of sensorial input. For example, OMM results in practitioners reporting an increase
604 in sensitivity of general physiological functions such as ability to feel their pulse, increased awareness
605 of breathing, temperature changes and bodily pressure changes across the ages (Vieten et al., 2018).
606 We consider this an important neurobiologically plausible mechanism that could help elder adults that
607 may have reduced function in peripheral structures. It suggests that OMM practice and the goal of
608 witnessing, may increase upregulation of bottom-up sensory information that may otherwise be
609 overpowered by cortical signals that stem from increased cognitive control due to deteriorated cortical
610 and subcortical structures. In other words, with OMM practice there is a possibility to upregulate
611 communications between perceptual processor and the central processor as outlined in the C-SMB. The
612 proposed mechanism is that elder adults with a state of weakened cognitive control from OMM, start
613 to “search” more creatively (Lippelt et al., 2014) for relational elements in the sequence and facilitate
614 greater R-R bindings that help to increase motor chunking processes (Amer et al., 2016; Anderson et
615 al., 2014). This in turn helps to more quickly build internalised sequence representations and quicker
616 motor sequence acquisition. In the only direct application with MSL, participants that practiced OMM
617 with less perceived effort prior to learning, showcased faster reaction time and increased sequence-
618 specific learning performance compared to participants performing FAM and a control task (Immink et
619 al., 2017). This is a promising outcome and warrants further investigation especially in our context of
620 enhancing MSL performance in elder adults.

621 In sum, we can expect FAM to induce states of increased cognitive control, whilst OMM would
622 induce states of weakened cognitive control. Given that elder adults typically exhibit cortical
623 compensation we propose that practicing OMM may be able to provide some cognitive benefit to MSL

624 which will contribute to a more wholistic individualised approach for MSL. In the next section, we
625 outline electrophysiological measures which would provide insight to cortical changes.

626 **4. Event-related desynchronization/ synchronization for individualisation of cognitive and** 627 **motor sequence learning**

628 In order to take the individualisation of MSL in elder adults to the next stage, assessment of the changes
629 that occur in the cortex alongside behavioural outcomes must be implemented. Whilst the use of event-
630 related potentials (ERP) has been utilized to investigate MSL (Daltrozzo & Conway, 2014; De Kleine
631 & Van der Lubbe, 2011) and effects of meditation on MSL (Chan et al., 2020), the method only provides
632 one form of approximation of cognitive processes related in a fixed time-delay to stimuli. The changes
633 in ERP are time-locked but not phase-locked, meaning that frequency specific changes of ongoing
634 electroencephalographic (EEG) activity in neuronal networks are not considered (Pfurtscheller & Lopes
635 da Silva, 1999). The increases and decreases in power for a specific bandwidth are an important
636 consideration because they reflect the synchrony of the underlying neuronal populations. Respectively,
637 decreases can be referred to as *event-related desynchronization* (ERD) and increases as *event-related*
638 *synchronization* (ERS) (Pfurtscheller & Lopes da Silva, 1999).

639 ERD/ERS oscillations are determined by intrinsic membrane properties and their dynamics,
640 which reflect the strength of network elements such as thalamo-cortical or cortico-cortical feedback
641 loops operating over short or long distances (Sigala et al., 2014). Combined with modulating influences
642 from general and immediate neurotransmitter systems, they give rise to different states of synchrony
643 and oscillations at different frequencies. In the case of EEG, frequencies are negatively correlated with
644 amplitude which means that slower oscillatory activity have larger amplitudes and vice versa; faster
645 oscillatory activity have smaller amplitudes (Pfurtscheller & Lopes da Silva, 1999). This kind of pattern
646 of the different frequencies are considered reflections of local interactions between main neurons and
647 interneurons driven by induced activity that are driven by processes related to cognitive control.
648 ERD/ERS is computed by comparing the period prior to stimuli and then the period following the
649 presentation of a stimuli, and expressed as a percentage of power decrease or increase (Karrasch et al.,
650 2004).

651 The ERD/ERS is a robust methodology due to its excellent temporal and spatial resolution for
652 investigating changes in elder adults during MSL. ERD refers to the phenomenon of oscillatory
653 components' relative to amplitude decreases from the moment of sensory and cognitive processing prior
654 to movement, and during movement (Li et al., 2018). The ERS is the opposite where relative amplitude
655 increases are evident from about ~one second post movement completion, most evident in the beta
656 bandwidth. In the next sub-sections we will expand on the two frequency bandwidths, alpha and beta
657 and review how it can inform of changes related to cognitive control during MSL alongside possible
658 effects from meditation that we would expect that enhances MSL.

659 4.1. Alpha event-related desynchronization and motor sequence learning in elder adults

660 Alpha is a dominant human EEG rhythm that has been associated with different cognitive processing
661 and the bandwidth ranges from 8 – 13 Hz (Corcoran et al., 2018; Haegens et al., 2014). Specifically,
662 we can expect that the changes in amplitude in the alpha bandwidth to broadly reflect cognitive demands
663 in attention and memory (dependant on topography) across different task during engagement, which
664 facilitates an understanding of how these process are being executed (Klimesch et al., 1993).
665 Specifically in MSL, the alpha rhythm that appears across the sensory-motor cortical areas is referred
666 to as μ (mu) or “Rolandic”/ somatosensory alpha rhythm reflect general readiness of neurons with
667 relation to movement preparation. This mu ERD that appears (~ two seconds pre-movement) on the
668 contralateral side of the cortex prior to movement, gives an indication for the strength of inhibitory
669 processes and priming needed to execute accurate forthcoming movement (Pfurtscheller & Lopes da
670 Silva, 1999; Pfurtscheller & Neuper, 2003). The mu ERD last for the duration of the movement and
671 can last a few seconds following cessation of movement (Kraeutner et al., 2014). It has been reported
672 that the upper bandwidth of mu ERD (10 – 13 Hz) is mainly sensitive to finger and wrist movements
673 and that lower bandwidth (8 – 10 Hz) is sensitive to larger bodily movement such as the foot and what
674 can be described as general motor attention (Klimesch, 1999; Pfurtscheller & Neuper, 2003).

675 Although mu ERD is particularly suitable to study MSL, there are no known studies that have
676 investigated changes in the DSP with elder adults, and only one relatively current study that sought to
677 understand implicit and explicit learning differences in the serial reaction time task (Zhuang et al.,
678 1997). It was found that the amplitude of mu ERD was greatest when explicit knowledge of the
679 sequence was first acquired, and as RT decreased in later learning so did the amplitude of mu ERD at
680 10 Hz. This corroborates with the understanding that well-acquired and fast MSL is associated with
681 lower amplitudes, inline what is referred to as the neural efficiency hypothesis (Bazanov & Vernon,
682 2014). In the elderly, we further drew upon evidence from a large open-access cohort dataset (567
683 participants) involving adults performing a simple button-press to understand the dynamics of mu ERD
684 (Bardouille & Bailey, 2019). In terms of spatial representation, the mu ERD amplitude difference was
685 less asymmetrical between the hemispheres with age, but that increased peak suppression amplitude
686 was expected with age. This is possibly signalling some form of compensation in elder adults for
687 inhibitory processes that may be required to prevent unnecessary movement not required for the task
688 (Sallard et al., 2016). Latency of the peak amplitude in mu ERD did not change with the factor of age
689 but this could be different when applied in a more complex task like the DSP. These outcomes are
690 particularly relevant for understanding the cognitive processes in elder adults during MSL as there is
691 potential to further unravel the effect of compensation in both the temporal and power aspects of the
692 signal and whether meditation practice affects these cognitive processes.

693 We also found no known studies that have investigated the effects of OMM on mu ERD during
694 MSL in elder adults. To recall, we provided evidence of OMM as a form of cognitive training that may

695 enhance the performance of cognitive tasks like MSL in the elderly. To investigate this notion in mu
 696 ERD, Chow et al. (2017), randomly assigned participants to three groups practicing either mindfulness
 697 meditation, alpha neurofeedback training or a sham alpha neurofeedback training groups for 15 minutes
 698 prior to performing a Stroop task. It was shown that there were no behavioural differences in Stroop
 699 task performance, although the Stroop task has also previously been reported to have a performance cap
 700 easily achieved in younger adults (Moore et al., 2012). However, it should be noted that mu ERD
 701 differed amongst the groups during Stroop performance, whereby mindfulness meditation participants
 702 had significantly lower amplitudes compared to the other two groups. This alludes to an earlier notion
 703 and suggest that some form of increased neural efficiency in Stroop performance could be expected
 704 following meditation.

705 Taken together, the evidence suggests that with increasing age, overall mu ERD amplitude is
 706 expected to increase but cortical activation will be less asymmetrical during performance of a simple
 707 movement related task. During MSL, we can expect mu ERD to firstly showcase increased amplitude
 708 during the learning phase and then decrease once learning has been automated. This pattern may appear
 709 in parallel with how motor cortical maps expand during learning and decrease back to baseline once a
 710 motor program has been acquired (Pascual-Leone et al., 1994).

711 **4.2. Beta event-related desynchronization and synchronization for motor sequence learning in** 712 **elder adults**

713 Oscillations in the beta frequency band (15–30 Hz) are thought to reflect changes in coherent activity
 714 and synchronous input from other brain regions such as prefrontal areas and SMA to M1 for the support
 715 of voluntary, passive and imagined movement (Jurkiewicz et al., 2006; Rossiter et al., 2014). Beta
 716 oscillatory activity occur in a similar temporal fashion to the mu rhythm. At rest, beta oscillations are
 717 present but approximately one second prior to movement, these rhythms are suppressed in what is
 718 known as beta ERD and usually last until movement is completed (Kraeutner et al., 2014). About one
 719 second after movement is completed, beta rhythm increases in amplitude (synchronize) with respect to
 720 the baseline period preceding movement known as post-movement *beta rebound*, which can last for
 721 approximately two seconds before returning to baseline (Cheyne, 2013; Gaetz et al., 2010). The beta
 722 rebound is localized to bilateral regions of the precentral gyrus but biased towards greater lateralization
 723 in the contralateral hemisphere to movement. It should be noted the with increasing age, the central
 724 beta frequency of ~20 Hz that usually exhibits the greatest activity in younger adults is expected to
 725 reduce in elder adults (Bardouille & Bailey, 2019). Peak amplitude of the beta rebound will reduce
 726 with age, and although peak latency is also expected to decline, it was not considered a significant
 727 characteristic compared to younger adults (Bardouille & Bailey, 2019).

728 Although the exact role of beta rhythms is still not fully understood, current evidence suggest
 729 that they are related to GABAergic inhibition and is predictive of movement-related outcomes (Gaetz
 730 et al., 2010; Rossiter et al., 2014). For example, in elder adults, increased levels of intracortical

731 GABAergic inhibition was positively correlated with mu and beta ERD and beta rebound. Evidence
732 suggest that with increasing age, there is a reduced capacity for plasticity from motor control and
733 practice, likely due to greater cortical inhibition processes (Muthukumaraswamy et al., 2013; Rossiter
734 et al., 2014; Tecchio et al., 2008). This may be linked with how elder adults approach MSL with a
735 focus on accuracy that tends to increase cognitive control leading to limited motor chunk development
736 (Verwey, 2010). With increased practise however, elder adults tend to develop use of motor chunks
737 (Barnhoorn et al., 2019), which may be an indication of elder adults ‘letting go of control’ later in
738 practice and reducing the impact of inhibitory processes associated with cognitive control.

739 In the absence of direct evidence of beta changes from MSL in the DSP task, we draw upon
740 other motor learning evidences. Espenhahn et al. (2019) utilized a continuous tracing task involving
741 wrist flexions and extensions through a predefined sequence of 12 position to investigate the dynamics
742 of beta oscillation differences between younger and apparently healthy elder adults. Each block
743 consisted of performing the sequence once and another random sequence and training was over a period
744 of 40 blocks. Root-mean-square-errors (movement kinematics) changes in the sequence were
745 considered sequence-specific, whilst random sequence changes were considered general learning. The
746 authors found that for behavioural movement kinematics, no statistical differences between younger
747 and elder adults were evident. However, elder adults exhibited greater lateralization, pre-movement
748 baseline power and greater beta ERD. Beta rebound power was not significantly different but increased
749 latency was found compared to younger adults. Movement-related beta ERD was not enhanced after
750 motor training, but this finding was not surprising given that previous evidence showed that oscillatory
751 activity increases are evident during training and should return back to baseline post-training (if training
752 was effective) (Pascual-Leone et al., 1994). Modelling revealed that movement-related beta ERD was
753 a predictor of better sequence-specific performance, whilst beta rebound was a predictor of general
754 learning performance. The results firstly supports the notion that beta ERD is likely to reflect
755 GABAergic inhibitory activity and that lower levels of activation are better for sequence-specific
756 learning – closely linked to what we proposed as a weakened cognitive control mechanism. The authors
757 speculated that the mechanism for beta rebound was likely closer to a reactive sensory afference (Engel
758 & Fries, 2010), in trying to predict future positions in uncertain random situations (Tan et al., 2016).
759 Combined, it seems to suggest that ongoing beta ERD could be closely related to motor chunking modes
760 and beta rebound related to reaction mode in elder adults with the C-SMB in mind.

761 Lastly, let us briefly outline some expected meditation-related changes in beta activity to
762 understand the kinds of enhancement which may affect elder adults in the absence of direct evidence.
763 The use of brain-controlled interfaces with EEG is increasingly being explored to help people who are
764 suffering from different kinds of neuromuscular disease to regain some movement ability when their
765 cognitive ability remains intact (Ang et al., 2015; Jiang et al., 2020). The most common techniques
766 include using sensorimotor oscillatory activity such as the mu rhythm, beta ERD and rebound from

767 EEG for decoding with algorithms that can eventually control physical objects such as wheel chairs as
768 bodily extensions (Huang et al., 2012; Trejo et al., 2006). There are basically two ways to enhance the
769 decoding of the signals: 1) to improve the algorithms and recording techniques; 2) to train the human
770 controller to generate higher quality/more decodable EEG signals (Eskandari & Erfanian, 2008; Jiang
771 et al., 2020; Stieger et al., 2020). Eskandari and Erfanian (2008) showed that meditators with about one
772 year of experience showcased more prominent beta ERD during movement imagery and beta rebound
773 post imagery compared to non-meditators. The decoding algorithm was also able to distinguish rest
774 and imagery states with 78.3% accuracy for non-meditators compared to 98.0% for meditators. These
775 results were repeated specifically again in OMM practitioners and that the time required to acquire the
776 ability to control competency over a computer cursor directional task was quicker than non-meditators
777 (Jiang et al., 2020; Stieger et al., 2020). These effects are promising and form a neurobiologically
778 plausible link for enhancement in beta oscillatory activity for elder adults. In the next section, we
779 combine the evidence presented thus far and formulate our modelling guidelines for work in this area.

780 **4.3. Modelling guidelines for compensatory mechanisms in elder adults**

781 In Section 2, we outlined that compensation is one of the ways by which cortical structures in elder
782 adults adapt to the demands of cognitive tasks for successful execution. Compensation can occur based
783 on increased activation to support intact structures, and/or remapping of function to other intact areas,
784 leading to a reduction in activation asymmetry (Cabeza, 2002; Cabeza et al., 2002). Although
785 compensation typically occurs, it does not necessarily lead to better performance in cognitive tasks and
786 MSL. There may be cases that despite increased cortical activation, motor performance is poor –
787 indicating that cortical compensation can be unsuccessful (Cabeza & Dennis, 2013). In other cases,
788 increased cortical activation can be coupled with better motor performance and hence we can conclude
789 that compensation was successful (Cabeza et al., 2002). Guided by these evidences, we can apply them
790 to MSL in elder adults and formulate modelling guidelines that will inform whether results obtained are
791 in line with better enhancement and performance in elder adults.

792

793

<Insert Figure 2. about here>



794

795 **Figure 2.** Based on current understanding of neurocognitive compensatory mechanisms in elder adults,
 796 we outline four possible conditions that may arise when elder adults perform motor sequence learning.
 797 This approach is also grounded on guidelines from the Cognitive framework for Sequential Motor
 798 Behavior (C-SMB) and will guide research that is motivated to understand the cognitive control
 799 activations that support motor sequence learning (MSL). It is also possible to predict changes following
 800 any interventions that is aimed to improve MSL performance. Favourable outcomes of compensation
 801 and MSL performance are highlighted in green and yellow boxes. Less favourable outcomes are
 802 highlighted in black and red.

803

804 Our population of interest are apparently healthy elder adults have predominately intact cortical
 805 structures and disease-free that participate in a generic MSL program. We base our assumption that
 806 these elder adults are performing MSL in a usual fashion without individualisation. It is possible that
 807 elder adults learning MSL end up in different states, affected by the manner that compensation occurs.
 808 Figure 2 provides a brief overview of these differences, but here we explain in detail. In an optimal
 809 scenario we can expect that some high performing elder adults exhibit cortical compensation that
 810 reduces the typical asymmetry seen between the hemispheres during cognitive tasks performance like
 811 the MSL (Cabeza, 2002; Cabeza et al., 2002; Cabeza & Dennis, 2013). We also predict that MSL
 812 performance in the form of RT to decrease, alongside an increase with the use of motor chunks to
 813 execute sequences by the end of training. With accordance to the C-SMB (Verwey et al., 2015),
 814 attention is minimally required as the responses required are motoric and executed automatically. The

815 pattern of cortical activation we would expect therefore is an increase in mu and beta ERD amplitudes
 816 during the learning phase and a reduction back to levels close to prior to learning. This would mean
 817 that a high level of behavioural learning expertise is coupled with relatively lower levels of cortical
 818 activation, similar to how younger adults perform their learning. We do not expect many elder adults
 819 to achieve this state without intervention via an individualised program aimed for optimisation.

820 In the 2nd scenario, we would also expect elder adults to also exhibit less cortical asymmetry
 821 during MSL. RT performance during MSL is expected to decrease alongside the development of motor
 822 chunks. The difference in this case is that mu ERD and beta ERD to remain elevated even after the
 823 learning phase and the development of motor chunks. This would indicate that a high level of
 824 behavioural learning expertise is coupled with relatively elevated levels of cortical activation. This is
 825 what Cabeza and Dennis (2013) refer to as *successful compensation* when elder adults are able to utilize
 826 more cognitive resources and continue to maintain a high level of performance in cognitive tasks like
 827 MSL. This state may not be the most neural efficient state, but it does mean that there is room for intervention
 828 via an individualised MSL approach.

829 In the 3rd scenario, elder adults exhibit less cortical asymmetry and higher cortical activation
 830 like in the 2nd scenario, but RT performance is much slower with less motor chunk development. In
 831 this case it would be referred to as *unsuccessful compensation* whereby elder adults are utilising more
 832 cognitive resources, but no behavioural performance improvements are evident. In the 4th scenario,
 833 cortical activation during MSL might fluctuate or remain low throughout the learning phase. The
 834 difference in this case is that mu and beta ERD remain low and that we can expect beta rebound to be
 835 elevated throughout learning and testing. This might indicate that elder adults are not engaged with
 836 MSL in that challenge might either be too high or too low to properly develop sequence representations.
 837 RT performance would be slow and there would be low development of motor chunks and with increase
 838 usage of reaction mode, indicating another case of unsuccessful compensation. Elder adults in scenario
 839 3 and 4 are hypothesised to gain the most benefit from an individualised MSL approach with OMM
 840 training. Using these four different scenarios to guide our modelling, we will be able to understand the
 841 dynamics of MSL in elder adults and increase the specificity in administering the right individualised
 842 training approach.

843 **5. Conclusion and hypotheses from Individualised COgnitive and Motor learning for the** 844 **Elderly (ICOME) framework**

845 Maintenance of motor control and learning is becoming an important goal across an aging world with
 846 increased longevity. We presented evidence on the aging processes in elder adults and how it affects
 847 general cognitive control and in turn MSL. In general, elder adults learn more slowly but have a
 848 potential to gain improved outcomes if more motor chunking is utilised. However, cognitive control
 849 and learning conditions need to be optimised for them to gain these benefits. There is a high potential

850 mechanism for OMM practise to induce states of weakened cognitive control that may reduce inhibitory
851 control effects and benefit MSL for elder adults. Recording accurate changes in cognitive control states
852 via ERD and ERS, is an important approach that will allow us to model cortical changes that ascertain
853 this and to predict behavioural performance. We take this opportunity to summarise with predictions
854 based on the presented theoretical and quantitative evidences and name our proposed approach as
855 *Individualised COgnitive and Motor learning for the Elderly (ICOME)*, aimed to enhance MSL over
856 generic programs.

857 *Hypothesis 1: The ICOME approach, which consists of progressive chunk implementation combined*
858 *with open-monitoring meditation, will improve motor chunk performance compared to a generic*
859 *program.*

860 This is supported from evidence from the C-SMB (Verwey et al., 2015) and behavioural
861 investigations from the C-SMB in elder adults (Barnhoorn, 2018; Barnhoorn et al., 2016; Barnhoorn et
862 al., 2019), highlighting the way elder adults learn differently. Our predictions include that OMM will
863 be able to induce weakened states of cognitive control prior to learning, that will improve the utilisation
864 of bottom-up feedback and inhibitory control during MSL. Firstly, we do not expect reaction time
865 differences between elder adults that participate in ICOME and those that do not due to possible
866 neuromuscular issues with stiff fingers affecting movement (Barnhoorn et al., 2019). However, we do
867 predict that the main difference from increased utilisation of motor chunks in elder adults that use the
868 ICOME approach gaining motor expertise without extended practise, compared to those that do not.

869 *Hypothesis 2: Motor sequence learning expertise in the form of reaction time will be predicted by beta*
870 *rebound variability, and the utilisation of motor chunks will be predicted by mu ERD and beta ERD*
871 *variability in elder adults.*

872 The current understanding of mu and beta oscillatory activity during MSL in the context of the
873 DSP task is not existent. However, guided by recent evidences from a wrist-movement sequence
874 learning (Espenhahn et al., 2019), and the reliability of predicting movement related outcomes from
875 these sensorimotor oscillations (Cheyne, 2013; Espenhahn et al., 2017; Gaetz et al., 2010), we have
876 reason to believe that it can uncover the neurocognitive mechanisms in MSL. Current evidence suggests
877 that reaction time performances if modelled with beta rebound could give an indication of general motor
878 performance and an indication of reaction mode being utilised. When further combined with mu and
879 beta ERD modelled with motor chunking performance, it could give a more wholistic picture of the
880 neurocognitive mechanism of how elder adults are developing their expertise and if internalised
881 representations are being developed adequately.

882 *Hypothesis 3: Elder adults that utilise the ICOME approach will result in greater reductions of mu and*
883 *beta ERD reductions following MSL and increased motor chunking, compared to others that utilise a*
884 *generic motor learning approach.*

885 In elder adults, we predict that utilising the ICOME approach with progressive-chunks and
886 OMM training would result in mu and beta ERD peak amplitudes to be lower than utilising a generic
887 MSL program by the end of training. In essence, this would indicate more neural efficient learning and
888 less inhibitory control states that result in better motor chunk development than generic MSL programs.
889 This interpretation is supported from current evidence for OMM, which suggest that states of weakened
890 cognitive control maybe resultant from practise and better support performance during MSL (Immink
891 et al., 2017; Lippelt et al., 2014). OMM meditation appears to help elder adults maintain cortical
892 structure (Luders, 2014; Luders et al., 2011) and cognitive function (Foulk et al., 2014; Gard et al.,
893 2014). In addition, research has found the meditators showcase clearer sensorimotor signals associated
894 with better control of brain-controlled interfaces compared to non-meditators (Eskandari & Erfanian,
895 2008; Stieger et al., 2020). Therefore, we predict that elder adults who participate in short term OMM
896 practise (Chan et al., 2020; Hinterberger et al., 2014) as part of an individualised program targeting
897 cognitive control, may be able gain these benefits for MSL.

898 **References:**

899

900 2020, H. (2018). *Work Programme 2018-2020: Health, demographic change and wellbeing*.
 901 [http://ec.europa.eu/research/participants/data/ref/h2020/wp/2018-2020/main/h2020-wp1820-
 health_en.pdf](http://ec.europa.eu/research/participants/data/ref/h2020/wp/2018-2020/main/h2020-wp1820-

 902 health_en.pdf)

903

904

905 (AWG), E. C. D. E. a. E. P. C. (2017). *The 2018 Ageing Report: Underlying Assumptions and
 906 Projection Methodologies*. [https://ec.europa.eu/info/sites/info/files/economy-
 finance/ip065_en.pdf](https://ec.europa.eu/info/sites/info/files/economy-

 907 finance/ip065_en.pdf)

908

909

910 Abrahamse, E., Braem, S., Notebaert, W., & Verguts, T. (2016, Jul). Grounding cognitive control in
 911 associative learning. *Psychol Bull*, 142(7), 693-728. <https://doi.org/10.1037/bul0000047>

912

913 Abrahamse, E. L., Ruitenberg, M. F., de Kleine, E., & Verwey, W. B. (2013). Control of automated
 914 behavior: insights from the discrete sequence production task. *Front Hum Neurosci*, 7, 82.
 915 <https://doi.org/10.3389/fnhum.2013.00082>

916

917 Abrahamse, E. L., van der Lubbe, R. H., & Verwey, W. B. (2008, Feb). Asymmetrical learning
 918 between a tactile and visual serial RT task. *Q J Exp Psychol (Hove)*, 61(2), 210-217.
 919 <https://doi.org/10.1080/17470210701566739>

920

921 Albouy, G., Sterpenich, V., Balteau, E., Vandewalle, G., Desseilles, M., Dang-Vu, T., Darsaud, A.,
 922 Ruby, P., Luppi, P. H., Degueldre, C., Peigneux, P., Luxen, A., & Maquet, P. (2008, Apr 24).
 923 Both the hippocampus and striatum are involved in consolidation of motor sequence memory.
 924 *Neuron*, 58(2), 261-272. <https://doi.org/10.1016/j.neuron.2008.02.008>

925

926 Allport, A. D., Styles, E. A., & Hsieh, S. (1994). *Shifting attentional set – Exploring the dynamic
 927 control of tasks* (Vol. Vol. XV).

928

929 Amer, T., Campbell, K. L., & Hasher, L. (2016, Dec). Cognitive Control As a Double-Edged Sword.
 930 *Trends Cogn Sci*, 20(12), 905-915. <https://doi.org/10.1016/j.tics.2016.10.002>

931

932 Amer, T., & Hasher, L. (2014). Conceptual Processing of Distractors by Older but Not Younger
 933 Adults. *Psychol Sci*, 25(12), 2252-2258. <https://doi.org/10.1177/0956797614555725>

934

935 Anderson, J. A., Campbell, K. L., Amer, T., Grady, C. L., & Hasher, L. (2014, Sep). Timing is
 936 everything: Age differences in the cognitive control network are modulated by time of day.
 937 *Psychol Aging*, 29(3), 648-657. <https://doi.org/10.1037/a0037243>

938

939 Ang, K. K., Chua, K. S. G., Phua, K. S., Wang, C., Chin, Z. Y., Kuah, C. W. K., Low, W., & Guan, C.
 940 (2015). A Randomized Controlled Trial of EEG-Based Motor Imagery Brain-Computer
 941 Interface Robotic Rehabilitation for Stroke. *Clin EEG Neurosci*, 46(4), 310-320.
 942 <https://doi.org/10.1177/1550059414522229>

943

- 944 Arking, R. (1998). *Biology of Aging: Observations and Principles*. Oxford University Press,
 945 Incorporated. <https://books.google.com.sg/books?id=dbnWRgAACAAJ>
- 946
- 947 Arnold, A., Wing, A. M., & Rotshtein, P. (2017, May). Building a Lego wall: Sequential action
 948 selection. *J Exp Psychol Hum Percept Perform*, 43(5), 847-852.
 949 <https://doi.org/10.1037/xhp0000382>
- 950
- 951 Bardouille, T., & Bailey, L. (2019, 2019/06/01/). Evidence for age-related changes in sensorimotor
 952 neuromagnetic responses during cued button pressing in a large open-access dataset.
 953 *Neuroimage*, 193, 25-34. <https://doi.org/https://doi.org/10.1016/j.neuroimage.2019.02.065>
 954
- 955
- 956 Barnhoorn, J. S. (2018). *Motor sequence learning in older adults* [University of Twente]. Enschede.
 957
- 958
- 959 Barnhoorn, J. S., Dohring, F. R., Van Asseldonk, E. H., & Verwey, W. B. (2016). Similar
 960 Representations of Sequence Knowledge in Young and Older Adults: A Study of Effector
 961 Independent Transfer. *Front Psychol*, 7, 1125. <https://doi.org/10.3389/fpsyg.2016.01125>
- 962
- 963 Barnhoorn, J. S., Van Asseldonk, E. H. F., & Verwey, W. B. (2019, 2019/03/01). Differences in
 964 chunking behavior between young and older adults diminish with extended practice. *Psychol*
 965 *Res*, 83(2), 275-285. <https://doi.org/10.1007/s00426-017-0963-6>
- 966
- 967 Bazanova, O. M., & Vernon, D. (2014, Jul). Interpreting EEG alpha activity. *Neurosci Biobehav Rev*,
 968 44, 94-110. <https://doi.org/10.1016/j.neubiorev.2013.05.007>
- 969
- 970 Biss, R. K., Ngo, K. W. J., Hasher, L., Campbell, K. L., & Rowe, G. (2013). Distraction Can Reduce
 971 Age-Related Forgetting. *Psychol Sci*, 24(4), 448-455.
 972 <https://doi.org/10.1177/0956797612457386>
- 973
- 974 Bo, J., Borza, V., & Seidler, R. D. (2009, Nov). Age-related declines in visuospatial working memory
 975 correlate with deficits in explicit motor sequence learning. *J Neurophysiol*, 102(5), 2744-
 976 2754. <https://doi.org/10.1152/jn.00393.2009>
- 977
- 978 Bostan, A. C., & Strick, P. L. (2010, Sep). The cerebellum and basal ganglia are interconnected.
 979 *Neuropsychol Rev*, 20(3), 261-270. <https://doi.org/10.1007/s11065-010-9143-9>
- 980
- 981 Broadbent, D. E. (1958). *Perception and communication*. Oxford University Press.
- 982
- 983 Brown, R. M., Robertson, E. M., & Press, D. Z. (2009, Aug 19). Sequence skill acquisition and off-
 984 line learning in normal aging. *PLoS One*, 4(8), e6683.
 985 <https://doi.org/10.1371/journal.pone.0006683>
- 986
- 987 Cabeza, R. (2001, Jul). Cognitive neuroscience of aging: contributions of functional neuroimaging.
 988 *Scand J Psychol*, 42(3), 277-286. <https://doi.org/10.1111/1467-9450.00237>
- 989

- 990 Cabeza, R. (2002, Mar). Hemispheric asymmetry reduction in older adults: the HAROLD model.
 991 *Psychol Aging*, 17(1), 85-100. <https://doi.org/10.1037/0882-7974.17.1.85>
- 992
- 993 Cabeza, R., Anderson, N. D., Locantore, J. K., & McIntosh, A. R. (2002, 2002/11/01/). Aging
 994 Gracefully: Compensatory Brain Activity in High-Performing Older Adults. *Neuroimage*,
 995 17(3), 1394-1402. <https://doi.org/https://doi.org/10.1006/nimg.2002.1280>
- 996
- 997 Cabeza, R., & Dennis, N. A. (2013). Frontal lobes and aging: Deterioration and Compensation. In D.
 998 T. Stuss & R. T. Knight (Eds.), *Principles of Frontal Lobe Function* (2nd ed., pp. 800).
 999 Oxford University Press.
- 1000
- 1001 Cabeza, R., Mangels, J., Nyberg, L., Habib, R., Houle, S., McIntosh, A. R., & Tulving, E. (1997,
 1002 1997/10/01/). Brain Regions Differentially Involved in Remembering What and When: a PET
 1003 Study. *Neuron*, 19(4), 863-870. [https://doi.org/https://doi.org/10.1016/S0896-6273\(00\)80967-](https://doi.org/https://doi.org/10.1016/S0896-6273(00)80967-8)
 1004 [8](https://doi.org/https://doi.org/10.1016/S0896-6273(00)80967-8)
- 1005
- 1006 Cahn, B. R., & Polich, J. (2006, Mar). Meditation states and traits: EEG, ERP, and neuroimaging
 1007 studies. *Psychol Bull*, 132(2), 180-211. <https://doi.org/10.1037/0033-2909.132.2.180>
- 1008
- 1009 Campbell, K. L., Zimmerman, S., Healey, M. K., Lee, M. M., & Hasher, L. (2012, Sep). Age
 1010 differences in visual statistical learning. *Psychol Aging*, 27(3), 650-656.
 1011 <https://doi.org/10.1037/a0026780>
- 1012
- 1013 Carmeli, E. (2017). Physical Therapy for Neurological Conditions in Geriatric Populations. *Front*
 1014 *Public Health*, 5, 333. <https://doi.org/10.3389/fpubh.2017.00333>
- 1015
- 1016 Chan, R. W., Alday, P. M., Zou-Williams, L., Lushington, K., Schlesewsky, M., Bornkessel-
 1017 Schlesewsky, I., & Immink, M. A. (2020, 2020/04/20/). Focused-attention meditation
 1018 increases cognitive control during motor sequence performance: Evidence from the N2
 1019 cortical evoked potential. *Behav Brain Res*, 384, 112536.
 1020 <https://doi.org/https://doi.org/10.1016/j.bbr.2020.112536>
- 1021
- 1022 Chan, R. W., Immink, M. A., & Lushington, K. (2017, Oct). The influence of focused-attention
 1023 meditation states on the cognitive control of sequence learning. *Conscious Cogn*, 55, 11-25.
 1024 <https://doi.org/10.1016/j.concog.2017.07.004>
- 1025
- 1026 Chan, R. W., Lushington, K., & Immink, M. A. (2018, Sep 18). States of focused attention and
 1027 sequential action: A comparison of single session meditation and computerised attention task
 1028 influences on top-down control during sequence learning. *Acta Psychol (Amst)*, 191, 87-100.
 1029 <https://doi.org/10.1016/j.actpsy.2018.09.003>
- 1030
- 1031 Cheyne, D. O. (2013, 2013/07/01/). MEG studies of sensorimotor rhythms: A review. *Experimental*
 1032 *Neurology*, 245, 27-39. <https://doi.org/https://doi.org/10.1016/j.expneurol.2012.08.030>
- 1033
- 1034 Chiesa, A., Calati, R., & Serretti, A. (2011, 2011/04/01/). Does mindfulness training improve
 1035 cognitive abilities? A systematic review of neuropsychological findings. *Clin Psychol Rev*,
 1036 31(3), 449-464. <https://doi.org/https://doi.org/10.1016/j.cpr.2010.11.003>

- 1037
 1038 Chow, T., Javan, T., Ros, T., & Frewen, P. (2017, 2017/06/01). EEG Dynamics of Mindfulness
 1039 Meditation Versus Alpha Neurofeedback: a Sham-Controlled Study. *Mindfulness (N Y)*, 8(3),
 1040 572-584. <https://doi.org/10.1007/s12671-016-0631-8>
- 1041
 1042 Corcoran, A. W., Alday, P. M., Schlesewsky, M., & Bornkessel-Schlesewsky, I. (2018, Jan 21).
 1043 Toward a reliable, automated method of individual alpha frequency (IAF) quantification.
 1044 *Psychophysiology*. <https://doi.org/10.1111/psyp.13064>
- 1045
 1046 Curran, T. (1997). Effects of aging on implicit sequence learning: accounting for sequence structure
 1047 and explicit knowledge. *Psychol Res*, 60(1-2), 24-41. <https://doi.org/10.1007/BF00419678>
 1048
- 1049
 1050 Daltrozzo, J., & Conway, C. M. (2014). Neurocognitive mechanisms of statistical-sequential learning:
 1051 what do event-related potentials tell us? *Front Hum Neurosci*, 8, 437.
 1052 <https://doi.org/10.3389/fnhum.2014.00437>
- 1053
 1054 Danielmeier, C., Eichele, T., Forstmann, B. U., Tittgemeyer, M., & Ullsperger, M. (2011, Feb 2).
 1055 Posterior medial frontal cortex activity predicts post-error adaptations in task-related visual
 1056 and motor areas. *J Neurosci*, 31(5), 1780-1789. [https://doi.org/10.1523/JNEUROSCI.4299-
 1057 10.2011](https://doi.org/10.1523/JNEUROSCI.4299-10.2011)
- 1058
 1059 Davidson, R. J., Kabat-Zinn, J., Schumacher, J., Rosenkranz, M., Muller, D., Santorelli, S. F.,
 1060 Urbanowski, F., Harrington, A., Bonus, K., & Sheridan, J. F. (2003, Jul-Aug). Alterations in
 1061 brain and immune function produced by mindfulness meditation [Clinical Trial
 1062 Comparative Study
 1063 Randomized Controlled Trial
 1064 Research Support, Non-U.S. Gov't
 1065 Research Support, U.S. Gov't, P.H.S.]. *Psychosom Med*, 65(4), 564-570.
 1066 <http://www.ncbi.nlm.nih.gov/pubmed/12883106>
- 1067
 1068 Davidson, R. J., & Kaszniak, A. W. (2015, Oct). Conceptual and methodological issues in research on
 1069 mindfulness and meditation. *Am Psychol*, 70(7), 581-592. <https://doi.org/10.1037/a0039512>
 1070
- 1071
 1072 Davis, S. W., Dennis, N. A., Buchler, N. G., White, L. E., Madden, D. J., & Cabeza, R. (2009, Jun).
 1073 Assessing the effects of age on long white matter tracts using diffusion tensor tractography.
 1074 *Neuroimage*, 46(2), 530-541. <https://doi.org/10.1016/j.neuroimage.2009.01.068>
- 1075
 1076 Dayan, E., & Cohen, L. G. (2011). Neuroplasticity subserving motor skill learning. *Neuron*, 72(3),
 1077 443-454. <https://doi.org/10.1016/j.neuron.2011.10.008>
- 1078
 1079 De Kleine, E., & Van der Lubbe, R. H. (2011, Mar). Decreased load on general motor preparation and
 1080 visual-working memory while preparing familiar as compared to unfamiliar movement
 1081 sequences. *Brain Cogn*, 75(2), 126-134. <https://doi.org/10.1016/j.bandc.2010.10.013>

- 1082
 1083 Doyon, J., Penhune, V., & Ungerleider, L. G. (2003). Distinct contribution of the cortico-striatal and
 1084 cortico-cerebellar systems to motor skill learning. *Neuropsychologia*, *41*(3), 252-262.
 1085 [https://doi.org/10.1016/s0028-3932\(02\)00158-6](https://doi.org/10.1016/s0028-3932(02)00158-6)
- 1086
 1087 Elsner, B., & Hommel, B. (2001, Feb). Effect anticipation and action control. *J Exp Psychol Hum*
 1088 *Percept Perform*, *27*(1), 229-240. <http://www.ncbi.nlm.nih.gov/pubmed/11248937>
 1089 <http://ovidsp.tx.ovid.com/ovftpdfs/FPDDNCGCJGEEIC00/fs046/ovft/live/gv023/00004788/0000478>
 1090 [8-200102000-00017.pdf](http://ovidsp.tx.ovid.com/ovftpdfs/FPDDNCGCJGEEIC00/fs046/ovft/live/gv023/00004788/0000478)
- 1091
 1092 Engel, A. K., & Fries, P. (2010, Apr). Beta-band oscillations--signalling the status quo? *Curr Opin*
 1093 *Neurobiol*, *20*(2), 156-165. <https://doi.org/10.1016/j.conb.2010.02.015>
- 1094
 1095 Eriksen, C. W., & St James, J. D. (1986, Oct). Visual attention within and around the field of focal
 1096 attention: a zoom lens model. *Percept Psychophys*, *40*(4), 225-240.
- 1097
 1098 Eskandari, P., & Erfanian, A. (2008, 20-25 Aug. 2008). Improving the performance of brain-computer
 1099 interface through meditation practicing. 2008 30th Annual International Conference of the
 1100 IEEE Engineering in Medicine and Biology Society,
- 1101
 1102 Espenhahn, S., de Berker, A. O., van Wijk, B. C. M., Rossiter, H. E., & Ward, N. S. (2017, Feb 15).
 1103 Movement-related beta oscillations show high intra-individual reliability. *Neuroimage*, *147*,
 1104 175-185. <https://doi.org/10.1016/j.neuroimage.2016.12.025>
- 1105
 1106 Espenhahn, S., van Wijk, B. C. M., Rossiter, H. E., de Berker, A. O., Redman, N. D., Rondina, J.,
 1107 Diedrichsen, J., & Ward, N. S. (2019, 2019/07/15/). Cortical beta oscillations are associated
 1108 with motor performance following visuomotor learning. *Neuroimage*, *195*, 340-353.
 1109 <https://doi.org/https://doi.org/10.1016/j.neuroimage.2019.03.079>
- 1110
 1111 Everly, G. S., & Lating, J. M. (2002). *A Clinical Guide to the Treatment of the Human Stress*
 1112 *Response*. Springer US. <https://books.google.com.au/books?id=wENVcfxt4BYC>
- 1113
 1114 Fontana, F. E., Furtado, O., Mazzardo, O., & Gallagher, J. D. (2009). Whole and Part Practice: A
 1115 Meta-Analysis. *Percept Mot Skills*, *109*(2), 517-530. <https://doi.org/10.2466/pms.109.2.517->
 1116 [530](https://doi.org/10.2466/pms.109.2.517-)
- 1117
 1118 Forstmann, B. U., Wagenmakers, E.-J., Eichele, T., Brown, S., & Serences, J. T. (2011, 2011/06/01/).
 1119 Reciprocal relations between cognitive neuroscience and formal cognitive models: opposites
 1120 attract? *Trends Cogn Sci*, *15*(6), 272-279.
 1121 <https://doi.org/https://doi.org/10.1016/j.tics.2011.04.002>
- 1122
 1123 Foulk, M. A., Ingersoll-Dayton, B., Kavanagh, J., Robinson, E., & Kales, H. C. (2014, 2014/07/04).
 1124 Mindfulness-Based Cognitive Therapy With Older Adults: An Exploratory Study. *Journal of*
 1125 *Gerontological Social Work*, *57*(5), 498-520. <https://doi.org/10.1080/01634372.2013.869787>
 1126
- 1127

- 1128 Franco, A., & Destrebecqz, A. (2012). Chunking or not chunking? How do we find words in artificial
 1129 language learning? *Adv Cogn Psychol*, 8(2), 144-154. [https://doi.org/10.2478/v10053-008-](https://doi.org/10.2478/v10053-008-0111-3)
 1130 [0111-3](https://doi.org/10.2478/v10053-008-0111-3)
- 1131
 1132 Friedman, N. P., & Miyake, A. (2004, Mar). The relations among inhibition and interference control
 1133 functions: a latent-variable analysis. *J Exp Psychol Gen*, 133(1), 101-135.
 1134 <https://doi.org/10.1037/0096-3445.133.1.101>
- 1135
 1136 Fuentes, C. T., & Bastian, A. J. (2007). 'Motor cognition' - what is it and is the cerebellum involved?
 1137 *Cerebellum (London, England)*, 6(3), 232-236. <https://doi.org/10.1080/14734220701329268>
 1138
- 1139
 1140 Gaetz, W., MacDonald, M., Cheyne, D., & Snead, O. C. (2010, 2010/06/01/). Neuromagnetic imaging
 1141 of movement-related cortical oscillations in children and adults: Age predicts post-movement
 1142 beta rebound. *Neuroimage*, 51(2), 792-807.
 1143 <https://doi.org/https://doi.org/10.1016/j.neuroimage.2010.01.077>
- 1144
 1145 Gallant, S. N. (2016, Feb). Mindfulness meditation practice and executive functioning: Breaking
 1146 down the benefit. *Conscious Cogn*, 40, 116-130. <https://doi.org/10.1016/j.concog.2016.01.005>
 1147
- 1148
 1149 Gard, T., Holzel, B. K., & Lazar, S. W. (2014, Jan). The potential effects of meditation on age-related
 1150 cognitive decline: a systematic review. *Ann N Y Acad Sci*, 1307, 89-103.
 1151 <https://doi.org/10.1111/nyas.12348>
- 1152
 1153 Grafton, S. T., Hazeltine, E., & Ivry, R. B. (1998, Nov 15). Abstract and effector-specific
 1154 representations of motor sequences identified with PET. *J Neurosci*, 18(22), 9420-9428.
 1155 <https://www.ncbi.nlm.nih.gov/pubmed/9801380>
- 1156
 1157 Gratton, G., Cooper, P., Fabiani, M., Carter, C. S., & Karayanidis, F. (2017, Oct 17). Dynamics of
 1158 cognitive control: Theoretical bases, paradigms, and a view for the future. *Psychophysiology*.
 1159 <https://doi.org/10.1111/psyp.13016>
- 1160
 1161 Haegens, S., Cousijn, H., Wallis, G., Harrison, P. J., & Nobre, A. C. (2014, May 15). Inter- and intra-
 1162 individual variability in alpha peak frequency. *Neuroimage*, 92, 46-55.
 1163 <https://doi.org/10.1016/j.neuroimage.2014.01.049>
- 1164
 1165 Hansell, S., & Mechanic, D. (1991, 1991/11/01). Body Awareness and Self-Assessed Health among
 1166 Older Adults. *Journal of Aging and Health*, 3(4), 473-492.
 1167 <https://doi.org/10.1177/089826439100300403>
- 1168
 1169 Hasenkamp, W., & Barsalou, L. W. (2012). Effects of meditation experience on functional
 1170 connectivity of distributed brain networks. *Front Hum Neurosci*, 6, 38.
 1171 <https://doi.org/10.3389/fnhum.2012.00038>
- 1172

- 1173 Heuninckx, S., Wenderoth, N., & Swinnen, S. P. (2008, Jan 2). Systems neuroplasticity in the aging
 1174 brain: recruiting additional neural resources for successful motor performance in elderly
 1175 persons. *J Neurosci*, 28(1), 91-99. <https://doi.org/10.1523/JNEUROSCI.3300-07.2008>
- 1176
 1177 Hinterberger, T., Schmidt, S., Kamei, T., & Walach, H. (2014, 2014-February-17). Decreased
 1178 electrophysiological activity represents the conscious state of emptiness in meditation
 1179 [Original Research]. *Front Psychol*, 5(99). <https://doi.org/10.3389/fpsyg.2014.00099>
- 1180
 1181 Hoffmann, J., & Koch, I. (1997, June 01). Stimulus-response compatibility and sequential learning in
 1182 the serial reaction time task [journal article]. *Psychol Res*, 60(1), 87-97.
 1183 <https://doi.org/10.1007/bf00419682>
- 1184
 1185 Holzel, B. K., Lazar, S. W., Gard, T., Schuman-Olivier, Z., Vago, D. R., & Ott, U. (2011, Nov). How
 1186 Does Mindfulness Meditation Work? Proposing Mechanisms of Action From a Conceptual
 1187 and Neural Perspective. *Perspect Psychol Sci*, 6(6), 537-559.
 1188 <https://doi.org/10.1177/1745691611419671>
- 1189
 1190 Hommel, B. (2000). *The prepared reflex: automaticity and control in stimulus-response translation*.
 1191 MIT Press.
- 1192
 1193 Hommel, B. (2015). Between Persistence and Flexibility: The Yin and Yang of Action Control. In A.
 1194 J. Elliot (Ed.), *Advances in Motivation Science* (Vol. 2, pp. 33-67). Elsevier.
 1195 <https://doi.org/https://doi.org/10.1016/bs.adms.2015.04.003>
- 1196
 1197 Hommel, B., & Colzato, L. S. (2017, June 01). Meditation and Metacontrol [journal article]. *Journal*
 1198 *of Cognitive Enhancement*, 1(2), 115-121. <https://doi.org/10.1007/s41465-017-0017-4>
- 1199
 1200 Howard, D. V., & Howard, J. H., Jr. (2001, Dec). When it does hurt to try: adult age differences in the
 1201 effects of instructions on implicit pattern learning. *Psychon Bull Rev*, 8(4), 798-805.
 1202 <https://doi.org/10.3758/bf03196220>
- 1203
 1204 Huang, D., Qian, K., Fei, D., Jia, W., Chen, X., & Bai, O. (2012). Electroencephalography (EEG)-
 1205 Based Brain-Computer Interface (BCI): A 2-D Virtual Wheelchair Control Based on Event-
 1206 Related Desynchronization/Synchronization and State Control. *IEEE Transactions on Neural*
 1207 *Systems and Rehabilitation Engineering*, 20(3), 379-388.
 1208 <https://doi.org/10.1109/TNSRE.2012.2190299>
- 1209
 1210 Immink, M. A., Colzato, L. S., Stolte, M., & Hommel, B. (2017, June 01). Sequence Learning
 1211 Enhancement Following Single-Session Meditation Is Dependent on Metacontrol Mode and
 1212 Experienced Effort [journal article]. *Journal of Cognitive Enhancement*, 1(2), 127-140.
 1213 <https://doi.org/10.1007/s41465-017-0019-2>
- 1214
 1215 Jafarpour, A., Piai, V., Lin, J. J., & Knight, R. T. (2017, 2017/07/20). Human hippocampal pre-
 1216 activation predicts behavior. *Scientific Reports*, 7(1), 5959. [https://doi.org/10.1038/s41598-](https://doi.org/10.1038/s41598-017-06477-5)
 1217 [017-06477-5](https://doi.org/10.1038/s41598-017-06477-5)
- 1218

- 1267 Klimesch, W. (1999, Apr). EEG alpha and theta oscillations reflect cognitive and memory
 1268 performance: a review and analysis. *Brain Res Brain Res Rev*, 29(2-3), 169-195.
 1269 <http://www.ncbi.nlm.nih.gov/pubmed/10209231>
- 1270
 1271 Klimesch, W., Schimke, H., & Pfurtscheller, G. (1993, Spring). Alpha frequency, cognitive load and
 1272 memory performance. *Brain Topogr*, 5(3), 241-251. <https://doi.org/10.1007/BF01128991>
 1273
- 1274
 1275 Koch, I., & Hoffmann, J. (2000, Jul). The role of stimulus-based and response-based spatial
 1276 information in sequence learning. *J Exp Psychol Learn Mem Cogn*, 26(4), 863-882.
 1277 <https://www.ncbi.nlm.nih.gov/pubmed/10946368>
- 1278
 1279 Koechlin, E., & Hyafil, A. (2007, Oct 26). Anterior prefrontal function and the limits of human
 1280 decision-making. *Science*, 318(5850), 594-598. <https://doi.org/10.1126/science.1142995>
- 1281
 1282 Koechlin, E., Ody, C., & Kouneiher, F. (2003, Nov 14). The architecture of cognitive control in the
 1283 human prefrontal cortex. *Science*, 302(5648), 1181-1185.
 1284 <https://doi.org/10.1126/science.1088545>
- 1285
 1286 Koechlin, E., & Summerfield, C. (2007, Jun). An information theoretical approach to prefrontal
 1287 executive function. *Trends Cogn Sci*, 11(6), 229-235.
 1288 <https://doi.org/10.1016/j.tics.2007.04.005>
- 1289
 1290 Kraeutner, S., Gionfriddo, A., Bardouille, T., & Boe, S. (2014, Nov 7). Motor imagery-based brain
 1291 activity parallels that of motor execution: evidence from magnetic source imaging of cortical
 1292 oscillations. *Brain Res*, 1588, 81-91. <https://doi.org/10.1016/j.brainres.2014.09.001>
- 1293
 1294 Kruger, M., Hinder, M. R., Puri, R., & Summers, J. J. (2017). Influence of Cognitive Functioning on
 1295 Age-Related Performance Declines in Visuospatial Sequence Learning. *Front Psychol*, 8,
 1296 919. <https://doi.org/10.3389/fpsyg.2017.00919>
- 1297
 1298 Kubica, J., Szymura, J., Domagalik, A., Golda, S., Wiecek, M., Fafrowicz, M., Marek, T., & Pera, J.
 1299 (2019, Nov 7). Systematic Balance Exercises Influence Cortical Activation and Serum BDNF
 1300 Levels in Older Adults. *J Clin Med*, 8(11). <https://doi.org/10.3390/jcm8111910>
- 1301
 1302 Lardone, A., Liparoti, M., Sorrentino, P., Rucco, R., Jacini, F., Polverino, A., Minino, R., Pesoli, M.,
 1303 Baseliçe, F., Sorriso, A., Ferraioli, G., Sorrentino, G., & Mandolesi, L. (2018, 2018/12/18).
 1304 Mindfulness Meditation Is Related to Long-Lasting Changes in Hippocampal Functional
 1305 Topology during Resting State: A Magnetoencephalography Study. *Neural Plasticity*, 2018,
 1306 5340717. <https://doi.org/10.1155/2018/5340717>
- 1307
 1308 Lazar, S. W., Kerr, C. E., Wasserman, R. H., Gray, J. R., Greve, D. N., Treadway, M. T., McGarvey,
 1309 M., Quinn, B. T., Dusek, J. A., Benson, H., Rauch, S. L., Moore, C. I., & Fischl, B. (2005,
 1310 Nov 28). Meditation experience is associated with increased cortical thickness. *Neuroreport*,
 1311 16(17), 1893-1897. <http://www.ncbi.nlm.nih.gov/pubmed/16272874>
- 1312 <http://ovidsp.tx.ovid.com/ovftpdfs/FPDDNCFBKBDODD00/fs047/ovft/live/gv031/00001756/000017>
 1313 [56-200511280-00005.pdf](http://ovidsp.tx.ovid.com/ovftpdfs/FPDDNCFBKBDODD00/fs047/ovft/live/gv031/00001756/000017)

- 1314
 1315 Lee, D. J., Kulubya, E., Goldin, P., Goodarzi, A., & Girgis, F. (2018). Review of the Neural
 1316 Oscillations Underlying Meditation. *Front Neurosci*, *12*, 178.
 1317 <https://doi.org/10.3389/fnins.2018.00178>
- 1318
 1319 Li, H., Huang, G., Lin, Q., Zhao, J. L., Lo, W. A., Mao, Y. R., Chen, L., Zhang, Z. G., Huang, D. F.,
 1320 & Li, L. (2018). Combining Movement-Related Cortical Potentials and Event-Related
 1321 Desynchronization to Study Movement Preparation and Execution. *Front Neurol*, *9*, 822.
 1322 <https://doi.org/10.3389/fneur.2018.00822>
- 1323
 1324 Lippelt, D. P., Hommel, B., & Colzato, L. S. (2014). Focused attention, open monitoring and loving
 1325 kindness meditation: effects on attention, conflict monitoring, and creativity - A review. *Front*
 1326 *Psychol*, *5*, 1083. <https://doi.org/10.3389/fpsyg.2014.01083>
- 1327
 1328 Luders, E. (2014, Jan). Exploring age-related brain degeneration in meditation practitioners. *Ann N Y*
 1329 *Acad Sci*, *1307*, 82-88. <https://doi.org/10.1111/nyas.12217>
- 1330
 1331 Luders, E., Clark, K., Narr, K. L., & Toga, A. W. (2011, Aug 15). Enhanced brain connectivity in
 1332 long-term meditation practitioners. *Neuroimage*, *57*(4), 1308-1316.
 1333 <https://doi.org/10.1016/j.neuroimage.2011.05.075>
- 1334
 1335 Luders, E., Phillips, O. R., Clark, K., Kurth, F., Toga, A. W., & Narr, K. L. (2012, 2012/05/15/).
 1336 Bridging the hemispheres in meditation: Thicker callosal regions and enhanced fractional
 1337 anisotropy (FA) in long-term practitioners. *Neuroimage*, *61*(1), 181-187.
 1338 <https://doi.org/https://doi.org/10.1016/j.neuroimage.2012.02.026>
- 1339
 1340 Lustig, C., Shah, P., Seidler, R., & Reuter-Lorenz, P. A. (2009, Dec). Aging, training, and the brain: a
 1341 review and future directions. *Neuropsychol Rev*, *19*(4), 504-522.
 1342 <https://doi.org/10.1007/s11065-009-9119-9>
- 1343
 1344 Lutz, A., Jha, A. P., Dunne, J. D., & Saron, C. D. (2015, Oct). Investigating the phenomenological
 1345 matrix of mindfulness-related practices from a neurocognitive perspective. *Am Psychol*,
 1346 *70*(7), 632-658. <https://doi.org/10.1037/a0039585>
- 1347
 1348 Lutz, A., Slagter, H. A., Dunne, J. D., & Davidson, R. J. (2008, Apr). Attention regulation and
 1349 monitoring in meditation. *Trends Cogn Sci*, *12*(4), 163-169.
 1350 <https://doi.org/10.1016/j.tics.2008.01.005>
- 1351
 1352 Malinowski, P. (2013). Neural mechanisms of attentional control in mindfulness meditation. *Front*
 1353 *Neurosci*, *7*, 8. <https://doi.org/10.3389/fnins.2013.00008>
- 1354
 1355 Mattay, V. S., Fera, F., Tessitore, A., Hariri, A. R., Das, S., Callicott, J. H., & Weinberger, D. R.
 1356 (2002, Feb 26). Neurophysiological correlates of age-related changes in human motor
 1357 function. *Neurology*, *58*(4), 630-635. <https://www.ncbi.nlm.nih.gov/pubmed/11865144>
 1358 <http://n.neurology.org/content/58/4/630.long>
 1359 <https://n.neurology.org/content/58/4/630.long>

- 1360
 1361 Mejia, S., Pineda, D., Alvarez, L. M., & Ardila, A. (1998, Sep). Individual differences in memory and
 1362 executive function abilities during normal aging. *Int J Neurosci*, 95(3-4), 271-284.
 1363 <http://www.ncbi.nlm.nih.gov/pubmed/9777444>
- 1364
 1365 Middleton, F. A., & Strick, P. L. (1998, Sep 1). Cerebellar output: motor and cognitive channels.
 1366 *Trends Cogn Sci*, 2(9), 348-354. [https://doi.org/10.1016/s1364-6613\(98\)01220-0](https://doi.org/10.1016/s1364-6613(98)01220-0)
- 1367
 1368 Miller, G. A., Galanter, E., & Pribram, K. H. (1960). Plans and the structure of behavior. By George
 1369 A. Miller, Eugene Galanter and Karl H. Pribram 1960. Henry Holt and company, New York.
 1370 226 pp. *Journal of Comparative Neurology*, 115(2), 217-217.
 1371 <https://doi.org/10.1002/cne.901150208>
- 1372
 1373 Moore, A., Gruber, T., Deroose, J., & Malinowski, P. (2012). Regular, brief mindfulness meditation
 1374 practice improves electrophysiological markers of attentional control. *Front Hum Neurosci*, 6,
 1375 18. <https://doi.org/10.3389/fnhum.2012.00018>
- 1376
 1377 Mund, I., Bell, R., & Buchner, A. (2012, 2012/01/01). Aging and Interference in Story Recall.
 1378 *Experimental Aging Research*, 38(1), 20-41. <https://doi.org/10.1080/0361073X.2012.636724>
 1379
- 1380
 1381 Muthukumaraswamy, S. D., Myers, J. F., Wilson, S. J., Nutt, D. J., Lingford-Hughes, A., Singh, K.
 1382 D., & Hamandi, K. (2013, Feb 1). The effects of elevated endogenous GABA levels on
 1383 movement-related network oscillations. *Neuroimage*, 66, 36-41.
 1384 <https://doi.org/10.1016/j.neuroimage.2012.10.054>
- 1385
 1386 Nations, U. (2019). *World Population Ageing 2019: Highlights*
 1387 <https://www.un.org/en/development/desa/population/publications/pdf/ageing/WorldPopulationAgeing2019-Highlights.pdf>
 1388
- 1389
 1390
 1391 Naylor, J. C., & Briggs, G. E. (1963). Effects of task complexity and task organization on the relative
 1392 efficiency of part and whole training methods. *J Exp Psychol*, 65(3), 217-224.
 1393 <https://doi.org/10.1037/h0041060>
- 1394
 1395 Nemeth, D., & Janacsek, K. (2011, Jan). The dynamics of implicit skill consolidation in young and
 1396 elderly adults. *J Gerontol B Psychol Sci Soc Sci*, 66(1), 15-22.
 1397 <https://doi.org/10.1093/geronb/gbq063>
- 1398
 1399 Nemeth, D., Janacsek, K., & Fiser, J. (2013). Age-dependent and coordinated shift in performance
 1400 between implicit and explicit skill learning. *Frontiers in computational neuroscience*, 7, 147-
 1401 147. <https://doi.org/10.3389/fncom.2013.00147>
- 1402
 1403 Nemeth, D., Janacsek, K., Polner, B., & Kovacs, Z. A. (2013). Boosting Human Learning by
 1404 Hypnosis. *Cerebral Cortex*, 23(4), 801-805. <https://doi.org/10.1093/cercor/bhs068>
 1405

- 1406 Newberg, A. B., Serruya, M., Wintering, N., Moss, A. S., Reibel, D., & Monti, D. A. (2014, Jan).
 1407 Meditation and neurodegenerative diseases. *Ann N Y Acad Sci*, 1307, 112-123.
 1408 <https://doi.org/10.1111/nyas.12187>
- 1409
 1410 Pascual-Leone, A., Grafman, J., & Hallett, M. (1994). Modulation of cortical motor output maps
 1411 during development of implicit and explicit knowledge. *Science*, 263(5151), 1287-1289.
 1412 <https://doi.org/10.1126/science.8122113>
- 1413
 1414 Peters, R. (2006, Feb). Ageing and the brain. *Postgrad Med J*, 82(964), 84-88.
 1415 <https://doi.org/10.1136/pgmj.2005.036665>
- 1416
 1417 Pfurtscheller, G., & Lopes da Silva, F. H. (1999, 1999/11/01/). Event-related EEG/MEG
 1418 synchronization and desynchronization: basic principles. *Clinical Neurophysiology*, 110(11),
 1419 1842-1857. [https://doi.org/https://doi.org/10.1016/S1388-2457\(99\)00141-8](https://doi.org/https://doi.org/10.1016/S1388-2457(99)00141-8)
- 1420
 1421 Pfurtscheller, G., & Neuper, C. (2003). Movement and ERD/ERS. In M. Jahanshahi & M. Hallett
 1422 (Eds.), *The Bereitschaftspotential: Movement-Related Cortical Potentials* (pp. 191-206).
 1423 Springer US. https://doi.org/10.1007/978-1-4615-0189-3_12
- 1424
 1425 Picard, N., & Strick, P. L. (1996, May-Jun). Motor areas of the medial wall: a review of their location
 1426 and functional activation. *Cereb Cortex*, 6(3), 342-353. <https://doi.org/10.1093/cercor/6.3.342>
 1427
- 1428
 1429 Pinotsis, D. A., Buschman, T. J., & Miller, E. K. (2018). Working Memory Load Modulates Neuronal
 1430 Coupling. *Cerebral Cortex*, 29(4), 1670-1681. <https://doi.org/10.1093/cercor/bhy065>
- 1431
 1432 Raz, N. (2000). Aging of the brain and its impact on cognitive performance: Integration of structural
 1433 and functional findings. In *The handbook of aging and cognition*, 2nd ed. (pp. 1-90).
 1434 Lawrence Erlbaum Associates Publishers.
- 1435
 1436 Rossiter, H. E., Davis, E. M., Clark, E. V., Boudrias, M. H., & Ward, N. S. (2014, May 1). Beta
 1437 oscillations reflect changes in motor cortex inhibition in healthy ageing. *Neuroimage*,
 1438 91(100), 360-365. <https://doi.org/10.1016/j.neuroimage.2014.01.012>
- 1439
 1440 Sallard, E., Tallet, J., Thut, G., Deiber, M.-P., & Barral, J. (2016, 2016/12/01). Age-related changes in
 1441 post-movement beta synchronization during a selective inhibition task. *Exp Brain Res*,
 1442 234(12), 3543-3553. <https://doi.org/10.1007/s00221-016-4753-y>
- 1443
 1444 Schmidt, R. A., & Wrisberg, C. A. (2008). *Motor learning and performance: a problem-based*
 1445 *learning approach*. (4th ed.). Human Kinetics.
- 1446
 1447 Schwab, J. F., Schuler, K. D., Stillman, C. M., Newport, E. L., Howard, J. H., & Howard, D. V.
 1448 (2016). Aging and the statistical learning of grammatical form classes. *Psychol Aging*, 31(5),
 1449 481-487. <https://doi.org/10.1037/pag0000110>
- 1450
 1451 Seidler-Dobrin, R. D., He, J., & Stelmach, G. E. (1998, Oct). Coactivation to reduce variability in the
 1452 elderly. *Motor Control*, 2(4), 314-330. <https://www.ncbi.nlm.nih.gov/pubmed/9758884>

- 1453
 1454 Seidler, R. D., Alberts, J. L., & Stelmach, G. E. (2002, Jan). Changes in multi-joint performance with
 1455 age. *Motor Control*, 6(1), 19-31. <https://www.ncbi.nlm.nih.gov/pubmed/11842268>
- 1456
 1457 Seidler, R. D., Bernard, J. A., Burutolu, T. B., Fling, B. W., Gordon, M. T., Gwin, J. T., Kwak, Y., &
 1458 Lipps, D. B. (2010, Apr). Motor control and aging: links to age-related brain structural,
 1459 functional, and biochemical effects. *Neurosci Biobehav Rev*, 34(5), 721-733.
 1460 <https://doi.org/10.1016/j.neubiorev.2009.10.005>
- 1461
 1462 Sigala, R., Haufe, S., Roy, D., Dinse, H. R., & Ritter, P. (2014). The role of alpha-rhythm states in
 1463 perceptual learning: insights from experiments and computational models. *Front Comput*
 1464 *Neurosci*, 8, 36. <https://doi.org/10.3389/fncom.2014.00036>
- 1465
 1466 Slagter, H. A., Davidson, R. J., & Lutz, A. (2011). Mental training as a tool in the neuroscientific
 1467 study of brain and cognitive plasticity. *Front Hum Neurosci*, 5, 17.
 1468 <https://doi.org/10.3389/fnhum.2011.00017>
- 1469
 1470 Stieger, J. R., Engel, S., Jiang, H., Cline, C. C., Kreitzer, M. J., & He, B. (2020). Mindfulness
 1471 Improves Brain–Computer Interface Performance by Increasing Control Over Neural Activity
 1472 in the Alpha Band. *Cerebral Cortex*. <https://doi.org/10.1093/cercor/bhaa234>
- 1473
 1474 Tan, H., Wade, C., & Brown, P. (2016, Feb 3). Post-Movement Beta Activity in Sensorimotor Cortex
 1475 Indexes Confidence in the Estimations from Internal Models. *J Neurosci*, 36(5), 1516-1528.
 1476 <https://doi.org/10.1523/JNEUROSCI.3204-15.2016>
- 1477
 1478 Tang, Y. Y., Holzel, B. K., & Posner, M. I. (2015, Apr). The neuroscience of mindfulness meditation.
 1479 *Nat Rev Neurosci*, 16(4), 213-225. <https://doi.org/10.1038/nrn3916>
- 1480
 1481 Tang, Y. Y., Lu, Q., Geng, X., Stein, E. A., Yang, Y., & Posner, M. I. (2010, Aug 31). Short-term
 1482 meditation induces white matter changes in the anterior cingulate. *Proc Natl Acad Sci U S A*,
 1483 107(35), 15649-15652. <https://doi.org/10.1073/pnas.1011043107>
- 1484
 1485 Tang, Y. Y., Ma, Y., Wang, J., Fan, Y., Feng, S., Lu, Q., Yu, Q., Sui, D., Rothbart, M. K., Fan, M., &
 1486 Posner, M. I. (2007, Oct 23). Short-term meditation training improves attention and self-
 1487 regulation. *Proc Natl Acad Sci U S A*, 104(43), 17152-17156.
 1488 <https://doi.org/10.1073/pnas.0707678104>
- 1489
 1490 Tanji, J. (1996, Dec). New concepts of the supplementary motor area. *Curr Opin Neurobiol*, 6(6),
 1491 782-787. [https://doi.org/10.1016/s0959-4388\(96\)80028-6](https://doi.org/10.1016/s0959-4388(96)80028-6)
- 1492
 1493 Tecchio, F., Zappasodi, F., Pasqualetti, P., Gennaro, L. D., Pellicciari, M. C., Ercolani, M., Squitti, R.,
 1494 & Rossini, P. M. (2008, 2008/03/01/). Age dependence of primary motor cortex plasticity
 1495 induced by paired associative stimulation. *Clinical Neurophysiology*, 119(3), 675-682.
 1496 <https://doi.org/https://doi.org/10.1016/j.clinph.2007.10.023>
- 1497
 1498 Trejo, L. J., Rosipal, R., & Matthews, B. (2006). Brain-computer interfaces for 1-D and 2-D cursor
 1499 control: designs using volitional control of the EEG spectrum or steady-state visual evoked

- 1500 potentials. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, 14(2), 225-
 1501 229. <https://doi.org/10.1109/TNSRE.2006.875578>
- 1502
 1503 Tubau, E., Hommel, B., & Lopez-Moliner, J. (2007, Feb). Modes of executive control in sequence
 1504 learning: from stimulus-based to plan-based control. *J Exp Psychol Gen*, 136(1), 43-63.
 1505 <https://doi.org/10.1037/0096-3445.136.1.43>
- 1506
 1507 Van der Lubbe, R. H. J., De Kleine, E., Schreurs, K. M. G., & Bohlmeijer, E. T. (2018). Does
 1508 mindfulness training modulate the influence of spatial attention on the processing of
 1509 intracutaneous electrical stimuli? *PLoS One*, 13(8), e0201689.
 1510 <https://doi.org/10.1371/journal.pone.0201689>
- 1511
 1512 Verwey, W. B. (1999). Evidence for a multistage model of practice in a sequential movement task.
 1513 *Journal of Experimental Psychology: Human Perception and Performance*, 25(6), 1693-
 1514 1708. <https://doi.org/10.1037/0096-1523.25.6.1693>
- 1515
 1516 Verwey, W. B. (2001, 2001/01/01/). Concatenating familiar movement sequences: the versatile
 1517 cognitive processor. *Acta Psychol (Amst)*, 106(1), 69-95.
 1518 [https://doi.org/https://doi.org/10.1016/S0001-6918\(00\)00027-5](https://doi.org/https://doi.org/10.1016/S0001-6918(00)00027-5)
- 1519
 1520 Verwey, W. B. (2010, Jun). Diminished motor skill development in elderly: indications for limited
 1521 motor chunk use. *Acta Psychol (Amst)*, 134(2), 206-214.
 1522 <https://doi.org/10.1016/j.actpsy.2010.02.001>
- 1523
 1524 Verwey, W. B., & Abrahamse, E. L. (2012, Jul). Distinct modes of executing movement sequences:
 1525 reacting, associating, and chunking. *Acta Psychol (Amst)*, 140(3), 274-282.
 1526 <https://doi.org/10.1016/j.actpsy.2012.05.007>
- 1527
 1528 Verwey, W. B., & Dronkert, Y. (1996, Mar). Practicing a Structured Continuous Key-Pressing Task:
 1529 Motor Chunking or Rhythm Consolidation? *J Mot Behav*, 28(1), 71-79.
 1530 <https://doi.org/10.1080/00222895.1996.9941735>
- 1531
 1532 Verwey, W. B., Jouen, A.-L., Dominey, P. F., & Ventre-Dominey, J. (2019, February 01). Explaining
 1533 the neural activity distribution associated with discrete movement sequences: Evidence for
 1534 parallel functional systems [journal article]. *Cognitive, Affective, & Behavioral Neuroscience*,
 1535 19(1), 138-153. <https://doi.org/10.3758/s13415-018-00651-6>
- 1536
 1537 Verwey, W. B., Lammens, R., & van Honk, J. (2002). On the role of the SMA in the discrete
 1538 sequence production task: a TMS study. *Transcranial Magnetic Stimulation*.
 1539 *Neuropsychologia*, 40(8), 1268-1276. [https://doi.org/10.1016/s0028-3932\(01\)00221-4](https://doi.org/10.1016/s0028-3932(01)00221-4)
- 1540
 1541 Verwey, W. B., Shea, C. H., & Wright, D. L. (2015, Feb). A cognitive framework for explaining
 1542 serial processing and sequence execution strategies. *Psychon Bull Rev*, 22(1), 54-77.
 1543 <https://doi.org/10.3758/s13423-014-0773-4>
- 1544
 1545 Vieten, C., Wahbeh, H., Cahn, B. R., MacLean, K., Estrada, M., Mills, P., Murphy, M., Shapiro, S.,
 1546 Radin, D., Josipovic, Z., Presti, D. E., Sapiro, M., Chozen Bays, J., Russell, P., Vago, D.,

- 1547 Travis, F., Walsh, R., & Delorme, A. (2018). Future directions in meditation research:
1548 Recommendations for expanding the field of contemplative science. *PLoS One*, *13*(11),
1549 e0205740. <https://doi.org/10.1371/journal.pone.0205740>
- 1550
1551 Williamon, A., & Valentine, E. (2000, Aug). Quantity and quality of musical practice as predictors of
1552 performance quality. *Br J Psychol*, *91* (Pt 3), 353-376.
1553 <https://doi.org/10.1348/000712600161871>
- 1554
1555 Zhuang, P., Toro, C., Grafman, J., Manganotti, P., Leocani, L., & Hallett, M. (1997, 1997/04/01/).
1556 Event-related desynchronization (ERD) in the alpha frequency during development of
1557 implicit and explicit learning. *Electroencephalogr Clin Neurophysiol*, *102*(4), 374-381.
1558 [https://doi.org/https://doi.org/10.1016/S0013-4694\(96\)96030-7](https://doi.org/https://doi.org/10.1016/S0013-4694(96)96030-7)
- 1559
1560