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Estimation of Intelligence Quotient in Healthy Individuals using Magnetic Resonance Imaging: A Systematic Review

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ABSTRACT

The intelligence quotient (IQ) is typically used to reflect human intelligence. Conventional IQ tests are commonly used to assess an individual's level of intelligence. However, the reliability of these conventional methods remains controversial as they are vulnerable to bias and often yield inconsistent results. Interestingly, emerging evidence suggested that magnetic resonance imaging (MRI) may be an alternative method to estimate a person's level of intelligence, as IQ is closely linked with the brain's structure. In this article, we systematically reviewed published studies on the estimation of IQ in healthy individuals using MRI. Following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines, a comprehensive search was performed in the PubMed database. The literature search focused on studies reporting on brain structures associated with IQ in healthy individuals and the effects of brain structural changes on IQ. 22 studies met the eligibility criteria and were included in this review. Key brain regions associated with IQ are grey matter (GM), white matter (WM), caudate nucleus, left hemisphere, limbic system, frontoparietal (FP) cortices, and default-mode network (DMN). The critical effect of ageing on brain changes and its impact on IQ were also discussed. Overall, the findings suggested that brain structures play a significant role in IQ levels in healthy individuals. This systematic review highlights the potential use of MRI in estimating IQ by examining brain structures. Nonetheless, available MRI studies were limited by methodological issues. Future MRI investigations should include well-characterized groups of females and matched male healthy individuals while considering confounding factors such as types of IQ tests.

Keywords: intelligence quotient, IQ estimation, magnetic resonance imaging, fMRI, brain structures

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1 INTRODUCTION

The intelligence quotient (IQ) is a score derived from standardised tests or subtests designed to assess human intelligence (Braaten & Norman, 2006). Generally, IQ reflects a person’s intelligence level, often measured using conventional IQ tests (Wang et al., 2015). Among the commonly used IQ tests are the Wechsler Adult Intelligence Scale (WAIS) and the Wechsler Intelligence Scale for Children (WISC) (Abiko et al., 2018). The IQ score acquired using these tests is a valid indicator of a person’s intelligence. However, most conventional IQ tests are prone to bias, contributing to the high degree of variability in the acquired IQ score (Wang et al., 2015). Moreover, most conventional IQ tests are mostly questionnaire-based and, thus, do not apply to children as they are not well-adapted to answering questionnaire-based assessments (Wang et al., 2015).

Research suggests that a person’s IQ can be better estimated using magnetic resonance imaging (MRI) rather than conventional IQ tests (Wang et al., 2015). The reason is that MRI can examine brain structures that are associated with IQ (DeSerisy et al., 2021). For instance, the brain's white matter (WM) volume is associated with information processing speed (Penke et al., 2012). Therefore, the volume of WM may reflect general intelligence as intelligent individuals process information faster than their counterparts (Penke et al., 2012). Another study also reported that the volume of the orbitofrontal cortex (OFC), cingulate gyrus, cerebellum, and thalamus were positively correlated with IQ scores (Wang et al., 2015). It is also important to note that brain morphology changes with ageing. As a person ages, the brain shrinks while the ventricles increase, implying that the amount of space filled by brain tissue in the head is now smaller than when the person was young (Davis, 2021). Hence, age-related brain tissue loss may also contribute to IQ declines in the elderly (Oschwald et al., 2019).

Apart from the WM volume, other brain characteristics, including surface area and gyrification (i.e., brain folds), also correlate with IQ (Tadayon et al., 2020). For instance, gyrification reduces as a person ages (Lamballais et al., 2020). As high IQ is associated with increased gyrification, a person’s IQ may decrease with age due to a reduction in gyrification (Lamballais et al., 2020). Consequently, the brain surface area may also decrease, resulting in the decline of a person’s IQ (Davis, 2021). Structural and functional MRI can provide insight into the ageing human brain and the effects of ageing on brain structures (Lockhart et al., 2014). Thus, by comparing the brains of young and old participants as well as the brains of the same people who have had their scans repeated over time, we may be able to understand better the neuro-biological basis for age-related cognitive changes as well as how changes in the brain can affect cognitive function.

Although these studies may have pointed out that MRI can better estimate IQ than conventional IQ tests, the brain regions associated with IQ have not been systematically summarised. Furthermore, more is needed to know about how brain structural changes due to ageing affect IQ levels in healthy individuals. Therefore, this review aims to identify the brain regions associated with IQ and discuss the effects of brain structural changes due to aging on IQ in healthy individuals.

2 METHODOLOGY

2.1 Research Strategy and Study Selection

The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines were used in conducting this review. The articles were searched and selected from the PubMed database. The literature search focused on studies reporting the brain structures associated with IQ in healthy individuals. Only studies published from 2015 to 2022 were included in this review. Search terms entered as follows: (((((IQ) AND (intelligence)) AND (healthy individuals)) AND (MRI)) NOT (review)) NOT (animal study). Initially, the PubMed database yielded 96 articles. None of these were duplicates. Afterwards, 54 articles were excluded based on the titles and abstracts because they were irrelevant to the study's objectives, leaving 42 articles for full-text review. Of these, 22 were accepted, while 20 were excluded because they did not meet the eligibility criteria. Among the excluded articles, 11 were rejected because they were about patients with mental illness, while seven were about clinical populations. The remaining two articles were unavailable. Therefore, a total of 22 articles were included in this review. The two researchers performed the screening and selection process to avoid selection bias. Should there be a disagreement between the researchers on the relevance of an article, a consensus was made through discussions. In this study, both researchers agreed that all the excluded articles were irrelevant to the study's objectives and did not meet the eligibility criteria. The PRISMA flow diagram illustrates the literature search process (Figure 1).

2.2 Inclusion and Exclusion Criteria

The following criteria shown in Table 1 were used to determine whether the study should be included or excluded from the review in determining the brain structures associated with IQ and the effects of brain structural changes in healthy individuals.

Table 1. Inclusion and exclusion criteria.

Inclusion criteria	Exclusion criteria
Studies on healthy individuals with normal cognitive functions	Review articles
Studies using MRI	Animal studies
Studies on brain structural changes, IQ, and aging	Studies on patients with mental illness
Peer-reviewed articles published between 2015 and 2022	
Articles written in English	

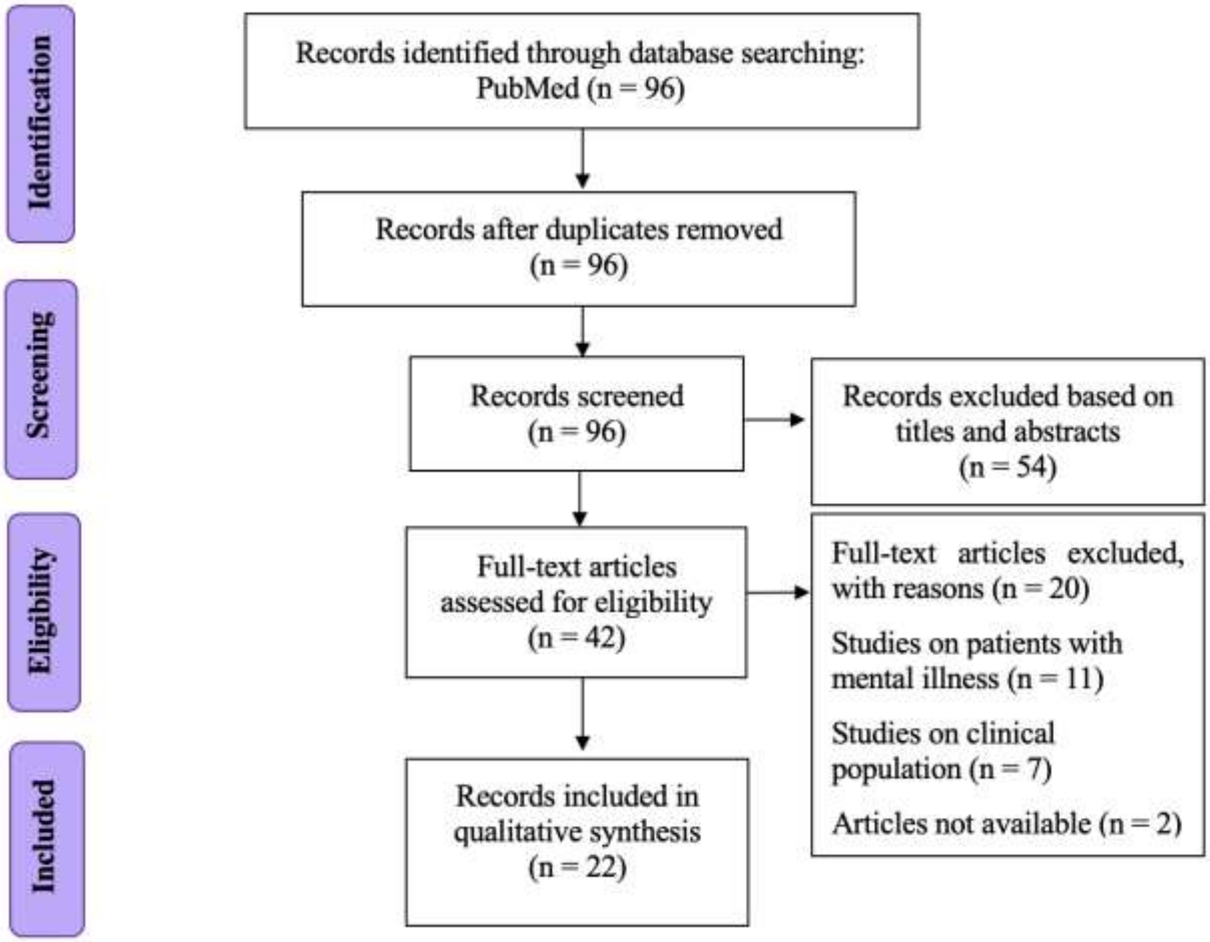

Figure 1. The PRISMA flow diagram for the systematic review

3 RESULTS

The characteristics of the 22 articles included in the review are shown in Table 2. Among the 22 articles, 15 articles discussed the association between brain structures and IQ (Backeljauw et al., 2015; Bajaj et al., 2018; DeSerisy et al., 2021; Grazioplene et al., 2015; Hidese et al., 2020; Koenis et al., 2015; King et al., 2015; Li et al., 2020; Malpas et al., 2016; Nestor et al., 2015; Ohtani et al., 2017; Raja et al., 2022; Santarnecchi et al., 2015; Schnack et al., 2015; Urger et al., 2015). Additionally, four articles reported on the brain structural changes associated with ageing (Baker et al., 2017; Hoffman et al., 2017; Santarnecchi et al., 2015; Zarnani et al., 2019), while the remaining three articles discussed other types of brain changes (Carpenter et al., 2016; Li et al., 2020; Margolis et al., 2018).

Table 2. Summary of studies on brain structures associated with IQ in healthy individuals.

No	Study	na	Ageb	Type of IQ test taken	Type of MRI	Brain structures associated with IQ	Changes in the brain anatomical structure	Effects on IQ
1.	Hidese et al. (2020)	266	45.6 ± 12.9	WAIS-III JART	VBM DTI	Grey matter (GM) volume White matter (WM) functional anisotropy (FA)	-	Increase
2.	Bajaj et al. (2018)	56	30.8 ± 8.1	WASI-II	Structural MRI	Cortical thickness (CT) (posterior frontal, superior parietal lobes) Cortical volume (CV) (temporal, posterior frontal, parietal lobes, inferior frontal gyrus (IFG))	-	Increase
3.	Jancke et al. (2020)	231	70.84 ± 5.08	German intelligence test	Structural MRI	GM volume Normal appearance white matter (NAWM)	Decrease GM Decrease NAWM	Decrease
4.	DeSerisy et al. (2021)	124	16.28 ± 4.73	WASI	fMRI	Fronto-parietal (FP) and default-mode network (DMN) connectivity are more anticorrelated and negative		Increase
5.	Li et al. (2020)	197	24.96 ± 4.44 (high IQ group) 29.83 ± 11.01 (general IQ group)	WAIS-RC	Resting-state fMRI	Resting-state functional connectivity (RSFC) between the right amygdala and right superior parietal RSFC between the right amygdala and the left middle cingulum	-	Increase
6.	Li et al. (2020)	30	64.5 ± 11.5	WAIS-III	Structural MRI	Dopamine transporter (DAT)	Decrease DAT	Decrease
7.	Nestor et al. (2015)	25	± 9.06	TMT WCS WAIS-III	Structural MRI	Bilateral GM volumes of the middle orbital gyrus Prefrontal GM volume		Increase
8.	Graziopleneet al. (2015)	517	26.2 ± 5.0	WAIS-IV WASI WASI-III	Structural MRI	Caudate volume	-	Increase

9.	Zarnani et al. (2019)	193	20-57	BP IST	DW-MRI Structural MRI	GM volume WM Total brain volume	Decrease total brain volume. Decrease WM Decrease GM	Decrease
10.	Malpas et al. (2016)	171	18-55	WASI	DTI Structural MRI	WM organisation Functional connectivity in large sub-networks (frontal regions and parietal regions)	-	Increase
11.	Schnack et al. (2015)	504	4.10 ±1.26	WISC-III WAIS WAIS-III-NL	Structural MRI	CT in the left hemisphere in adults CT in children Cortical surface area (CSA) CV	-	Increase
12.	Backeljauw et al. (2015)	53	5-18	OWLS WAIS	Structural MRI	Occipital cortex GM density Cerebellum GM density Frontal lobe GM density	-	Decrease
13.	Ohtani et al. (2017)	26	38.62 ± 10.61	WAIS-III TMT WCST	DTI	GM orbito-frontal cortex (OFC) volume Left posterior mOFC-rACC WM FA Middle orbital gyrus GM Left hemisphere	-	Increase
14.	Carpenter et al. (2016)	39	2.74 ±0.9	DAS	Structural MRI	Iron in the right caudate	-	Increase
15.	Margolis et al. (2018)	55	16.1 ±3.8	WASI	fMRI	Functional connectivity from right IFG to right thalamus Connectivity from right IFG to right supramarginal gyrus (SMG). Activations in fronto-striatal, temporal, and limbic regions. Activations of limbic regions (hippocampus and amygdala) Activation of bilateral superior and anterior frontal cortices	-	Greater verbal intelligence quotient (VIQ) > performance intelligence quotient (PIQ) discrepancy

16.	King et al. (2015)	54	22.7±4.5	WASI	DTI Structural MRI	WM integrity	-	Decrease
17.	Santarnecchi et al (2015)	119	33±13	WASI WAIS WISC-IV	fMRI	Voxel-mirrored homotopic connectivity (VMHC) Interhemispheric connectivity	-	Increase
18.	Koenis et al. (2015)	120	2.92±0.23	WISC-III	Structural MRI DTI	WM FA GM density FA-based efficiency in frontal and temporal nodes Functional connectivity of the prefrontal cortex (PFC) and the rest of the brain Local network efficiency in the: Left inferior OFC. Left anterior cingulum. Right-sided frontal areas Superior temporal poles Insula Thalamus Putamen Pallidum Caudate nucleus	-	Increase
19.	Hoffman et al. (2017)	556	72.68 ±0.72	NART WTAR	DTI Structural MRI	WM GM Ventral temporal (VT) cortices FA of arcuate fasciculus	Decrease of VT cortices volume and thickness Decrease GM volume. Decrease in the FA of arcuate fasciculus.	Decrease
20.	Raja et al. (2022)	71	8(7.5-8.5)	RIAS	DW-MRI	WM	-	Increase
21.	Baker et al. (2017)	63	63.13±8.23	RBANS	Structural MRI DTI	WM	Shorter WM fiber bundle length (FBL)	Decrease
22.	Urger et al. (2015)	49	11.08±3.49	WPPSI-III WISC-III WASI	DTI	WM of superior longitudinal fasciculus (SLF)	-	Increase

[a] Total number of participants
[b] Age reported as mean ± SD, median (interquartile range) or median (range)

Abbreviations: BP = Børge Priens Test, CSA = cortical surface area, CT = cortical thickness, CV = cortical volume, DAS = Differential Abilities Scale, DAT = striatal dopamine transporter, DMN = default mode networks, DTI = Diffusion tensor imaging, DW = diffusion weighted, FA = functional anisotropy, FBL = fiber bundle length, fMRI = functional magnetic resonance imaging, FP = frontoparietal, GM = grey matter, IFG = inferior frontal gyrus, IQ = intelligence quotient, IST = Intelligenz-Struktur-Test, JART = Japanese Adult Reading Test, mOFC = medial orbital frontal cortex, MRI = magnetic resonance imaging, NAWM = normal appearing white matter, Nart = National Adult Reading Test, OFC = orbito-frontal cortex, OWLS = Oral and Written Language Scales, PFC = prefrontal cortex, rACC = rostral anterior cingulate cortex, RBANS = Repeatable Battery for the Assessment of Neuropsychological Status, RIAS = Reynolds Intellectual Assessment Scales, RSFC = resting-state functional connectivity, SLF = superior longitudinal fasciculus, SMG = supramarginal gyrus, TMT = Trail Making Test, VBM = Voxel-based morphometry, VHMC = voxel-mirrored homotopic connectivity, VT = ventral temporal, WAIS = Wechsler Adult Intelligence Scale, WASI = Wechsler Abbreviated Scale of Intelligence, WCST = Wisconsin Card Sorting Test, WISC = Wechsler intelligence scale for children, WISC = Wechsler Intelligence Scale for Children, WM = white matter, WPPSI = Wechsler Preschool and Primary Scale of Intelligence, WTAR = Wechsler Test of Adult Reading

4 DISCUSSION

Conventional IQ tests are not the best indicators of human intelligence level because they have the potential to inaccurately measure an individual’s intelligence (Shuttleworth-Edwards et al., 2004). Plus, IQ is insufficient to measure a person’s performance in cognitively demanding tasks (Ganuthula et al., 2019). Most IQ tests are also not suitable for children because they assess aptitudes that young children have not yet fully developed (Wang et al., 2015). Moreover, conventional IQ tests are insensitive to brain structural changes caused by healthy aging (Wang et al., 2015). The difference in the level of intelligence of an individual is influenced by the brain structures, which can be identified using MRI (Wang et al., 2015). Thus, MRI can potentially estimate the human intelligence level and help to identify children who are at risk of being cognitively challenged (Ganuthula et al., 2019). As such, MRI could be a more systematic method to assess or forecast an individual’s IQ (Wang et al., 2015).

The WM is made up of myelin, which is the white fatty sheaths that form the oligodendrocytes (Giedd et al., 2010; Penke et al., 2012). The oligodendrocytes surround axons and significantly increase neuronal signals by preventing signal leakage and reducing energy consumption (Giedd et al., 2010). An increase in WM leads to greater myelination and denser axon packing (Penke et al., 2012). Additionally, well-connected WM enables good neural circuitry integration and more effective information processing within extensive brain structures responsible for good cognitive functioning (Penke et al., 2012). The more effective the information processing, the better the information flow between different brain regions, thus leading to an increase in IQ (Salthouse, 1996).

Other than the WM, the grey matter (GM) volume has also been found to be positively correlated with IQ. In particular, GM volume increases as IQ increases. The outermost layer of the brain is made up of GM, which derives its grey colour from a dense concentration of neuronal cell bodies. The GM forms the gyri and sulci to increase the brain surface area. The increase in GM also increases the gyrification and sulci of the brain, leading to an increase in surface area. The increase in brain surface area accommodates more neurons, which is essential for efficient functioning. Numerous neurons in the GM enable it to process information and release new information via axon signalling present in the WM (Chiao et al., 2020). With this, the increase in GM volume leads to an increase in intelligence.

According to the parietal-frontal integration theory (P-FIT), high intelligence is associated with rapid and precise information transfer between the parietal and frontal lobes (Jung & Haier, 2007). The brain regions commonly associated with the P-FIT theory are the prefrontal cortex (PFC), temporoparietal cortex, superior parietal cortex, middle cingulum, and inferior frontal gyrus (IFG). These regions are important for cognitive processes that contribute to intelligence (Li et al., 2020; Othman et al., 2020). The theory proposed that an increase in both cortical thickness and volume of these brain regions contributes to the high IQ level (Jung and Haier, 2007; Bajaj et al., 2018). The WM in the parietal-frontal cortex (PFC) is larger than any other region (Schenker et al., 2005). One of the plausible reasons for this is that the PFC plays a key role in high-order cognitive processing (Friedman et al., 2021; Othman et al., 2019). The bilateral PFC was also found to be activated when individuals carried out a task involving a novel method of information decomposition (Huang et al., 2015). Meanwhile, the superior parietal cortex is involved in attention and spatial processing, while the middle cingulum is involved in attention and working memory (Han et al., 2004; Bubb et al., 2018). Therefore, an increase in the cortical thickness and volume of these regions may increase one's cognitive abilities and intelligence.

Apart from these brain regions, an fMRI study shows that the fronto-parietal (FP) and default-mode networks (DMN) functional connectivity may also play a crucial role in intelligence (Fox et al., 2005). The FP network is a task-positive network that normally activates during cognitively demanding tasks. Contrarily, the DMN is considered a task-negative network as it is commonly activated when a person is at rest (i.e., not engaging in a cognitively demanding task) (Raichle et al., 2001). According to studies, increased functional connectivity between these networks is associated with improved performance on cognitive control tasks (Abdul Wahab et al. 2022, Sheffield et al., 2015). It has been suggested that these networks work together in processing a highly cognitively demanding task without getting distracted by internal thoughts (Posner et al., 2014). As such, healthy individuals with high IQ levels demonstrated better connectivity between these two networks as compared to those with low IQ levels (DeSerisy et al., 2021).

Another fMRI study by Santarnecchi et al. (2015) shows that reduced voxel-mirrored homotopic activity (VMHC) and increased interhemispheric connectivity (e.g., frontoparietal interaction) are related to increases in IQ. VMHC is the degree of similarity or coherence in the functional activity between corresponding brain regions in the left and right hemispheres (Li et al., 2021). When VMHC is reduced, it indicates more stable and efficient communication between the two hemispheres (Wang et al., 2021). Besides, some models suggest that the left and right sides of the brain work against each other, but newer models suggest that the two sides work together to help the brain process information more efficiently (Banich & Brown, 2000). This happens because the two sides communicate and work together to handle different parts of a task at the same time (Liederman & Meehan, 1986).

The limbic system is commonly known for its role in emotional processing. One of the prominent brain structures in the limbic system is the amygdala, which is involved in emotional processing and regulation (Simic et al., 2021). The amygdala has also been associated with advanced cognitive abilities (e.g., decision-making, learning, attention, and working memory) (Bechara et al., 2003; Schaefer & Gray, 2007). A study reported that the functional connectivity between the right amygdala and the right superior parietal lobule (SPL) significantly mediated the association between comprehension and object assembly (Li et al., 2020). The study also found that the functional connectivity between the right amygdala and the left middle cingulum mediated the association between similarity and digit symbols. According to Mazhirina et al. (2016), the SPL is activated when participants perform tasks involving speech intelligibility, word memory, and manipulation of information. This modulation may facilitate more efficient processing and enhance cognitive performance (Li et al., 2020).

The caudate nucleus is another brain structure of the limbic system. It is primarily involved in many cognitive processes that are essential for higher intellectual functioning (e.g., learning and memory, attention, and decision-making) (Chiu et al., 2017). It also regulates the production of dopamine — a neurotransmitter that plays a critical role in cognitive processes (Nakamura et al., 2006). Dopamine is involved in motivation, reward processing, and attention (Bromberg-Martin et al., 2010; Deyoung et al., 2013). Thus, differences in caudate nucleus volume observed between individuals with high and low IQ levels may be related to differences in dopamine regulation, which in turn affect cognitive functioning (Grazioplene et al., 2015).

The brain hemisphere may also be a crucial factor underlying intelligence. For instance, a study demonstrated a relationship between the left cortex and intelligence level (Schnack et al., 2015). Specifically, the study reported that in adults with low IQ levels (i.e., less than 110), the left hemisphere continues to get thinner after the age of 21 years. On the contrary, the left hemisphere gets thicker in adults with high IQ levels (i.e., more than 110). The study added that by the age of 42, having a higher cortical thickness in the left brain hemisphere was linked to greater intelligence in these individuals (Schnack et al., 2015). This finding is reasonable considering that the left brain hemisphere is involved in complex cognitive processes underlying intelligence (e.g., in speech production, language comprehension, arithmetics, and logical reasoning) (Corballis et al., 2014; Hartwigsen et al., 2021).

As people get older, their intelligence level declines more than when they were young (Salthouse, 2009). The decline in cognitive abilities can follow a similar pattern as the development of cognitive abilities (Ferreira et al., 2017). The development and deterioration of cognitive ability may be influenced by changes in brain structures (Murman, 2015). Factors that may affect intelligence are the decreased brain volumes and thickness associated with healthy aging. As people age, the WM and GM volumes decrease. Large WM and GM volumes contain more neurons that are crucial for human intelligence and cognition (Langer et al., 2012). As compared to those with small WM volumes, subjects with larger WM volumes were found to score higher on an IQ test and demonstrated better cognitive ability (Wheater et al., 2021). Thus, IQ levels decrease as a consequence of reduced WM and GM volume due to healthy aging (Jancke et al., 2020).

In addition to brain volumes, the length of the WM fiber tract is also reduced in elderly individuals (Baker et al., 2017). The WM fiber tracts across are associated with fluid intelligence (Gf) (Chen et al., 2020). According to earlier studies, induction, quantitative reasoning, visualization, and problem-solving are all complex cognitive abilities associated with Gf (Duncan et al., 2017). As people grow older, the WM fiber tracts and Gf decrease (Hoffman et al., 2017). Moreover, Gf is also associated with GM (Shokri-Kojori et al., 2021). Individuals who had lower GM volumes exhibited lower Gf than their peers, indicating that Gf may likely be influenced by GM volumes (Shokri-Kojori et al., 2021). Additionally, a study discovered an association between GM volumes in the anterior temporal cortex and semantic abilities in older people (de Zubicaray et al., 2011). Semantic memory is a term used to describe knowledge of the meaning of words, objects, and facts. It is a crystallize ability responsible for knowledge, that increases because of daily experience, engagement in culture, and working (Bertola et al., 2019). Semantic memory typically lasts from adulthood until extremely old age (Kintz et al., 2017).

Worthy of note, this review has several limitations. Firstly, most studies included both male and female participants. The inclusion of both genders in the studies may have confounded the findings as males and females frequently exhibit different developmental trajectories for cognitive abilities and brain morphology measurements. In addition, the studies included in this review use various types of IQ tests (e.g., WAIS-III, WASI, JART) to test the level of intelligence of the participants. This might affect the bias on the results of the IQ tests, which might affect the consistency of the results of the study. Lastly, the studies included in this review have not discussed in-depth the reasons for choosing the different types of neuroimaging techniques (e.g. structural, functional, or DTI). As such, we could not comment on the reasons for using the different types of these techniques in the studies. However, we speculated that the structural MRI was used to investigate the brain's morphological structures (e.g. brain’s structural integrity and volume). On the other hand, DTI was used in those studies to examine the fiber tract in the brain (i.e. tractography). Meanwhile, fMRI was used to study the brain’s activity and functional connectivity. Future works should discuss the reasons for using a certain type of neuroimaging technique in their works. The information would be helpful to researchers, particularly those who are new to this field, to determine the best or appropriate neuroimaging techniques for their work.

5 CONCLUSION

With the use of MRI, the intelligence level of an individual and the brain changes effect can be estimated through the brain structures and functions instead of using conventional IQ tests. The findings from this systematic review show that brain structures can influence the intelligence level of an individual. The results from the 22 studies are mostly consistent. The brain characteristics influencing intelligence are GM, WM, left hemisphere, frontoparietal cortices, limbic system, FP network, DMN, and functional connectivity. Moreover, the brain changes when aging and the effect on IQ can also be explained using MRI. However, MRI can provide insights into brain structures and functions related to intelligence, it cannot directly generate an individual's IQ score. Nevertheless, studies suggested that MRI can potentially be used as an alternative tool in estimating IQ in healthy individuals.

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