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Inspection time and intelligence: A five-wave longitudinal study from age 70 to age 82 in the Lothian Birth Cohort 1936

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ABSTRACT

To test the idea that the slowing of simple information processing contributes to more general cognitive ageing, it is necessary to demonstrate that changes in the two variables are correlated as people grow older. Here, we examine the association between inspection time—a psychophysical measure of visual information processing—and general cognitive ability and the cognitive domains of visuospatial reasoning, processing speed, memory, and crystallised ability across five waves of testing in a 12-year period. The participants were members of the Lothian Birth Cohort 1936; there was a maximum of 1090 people with cognitive data at age 70 (Wave 1) and 426 at age 82 (Wave 5). At each testing wave the participants took the same 12 cognitive tests. Latent growth curve modelling in a structural equation modelling framework was used to examine the associations between intercepts and slopes of inspection time and other cognitive capabilities. Age-related changes (slope) in inspection time correlated 0.898 ($p < 0.001$) with changes (slope) in general cognitive ability over the 12 years. Inspection time changes correlated with changes in each of the four cognitive domains, but these associations were reduced to non-significance once the domains' loadings on general cognitive ability were taken into account (with the possible exception of memory, whose changes still had a marginal additional association with inspection time changes; $\beta = 0.199$, $p = 0.030$). The results are compatible with the idea that age-related slowing of processing speed contributes causally to the age-related declines in complex cognitive capability, but this is not the only interpretation of the present findings.

1. Introduction

It is important to understand why some people's cognitive skills decline more than others' as they grow older. On average some cognitive capabilities decline with age, especially after middle age (Salthouse, 2010). These fluid cognitive capabilities include aspects of memory and reasoning, and processing speed (Tucker-Drob et al., 2022). Crystallised cognitive capabilities, such as vocabulary and general knowledge show less mean decline with age (Tucker-Drob et al., 2022). Not everyone declines in all cognitive skills at the same rate in older age (Tucker-Drob, 2019). People who retain their cognitive skills at higher levels are more likely to cope with the tasks of living independently (Tucker-Drob, 2011). Therefore, as well as charting the mean levels of and individual differences in age-related cognitive changes, there is an interest in factors that associate with such differences (Corley, Cox, & Deary, 2018; Walhovd, Lövden, & Fjell, 2023). We use the phrase 'associate with' rather than 'cause' because the former is easier to demonstrate than the latter, and cause should not be presumed.

One of the associates of age-related changes in higher-level cognitive ability is so-called 'processing speed' (Salthouse, 1996; Verhaeghen, 2013). Though we shall use this term here, we acknowledge that it presents at least two difficulties (Deary & Ritchie, 2014). First, it is a general term for a number of different cognitive tasks. Processing speed tests tend to share the characteristic that they involve a measurement of how quickly people can complete simple cognitive items. However, tasks and tests that attract the processing speed label include psychometric tests (such as Wechsler Digit Symbol [Wechsler, 1998a] and similar tests), tasks from experimental and cognitive psychology (such as various reaction time procedures), and tasks from psychophysics (such as inspection time) (Deary, 2001; Jensen, 2006). The completion time for items in these types of task tends, respectively, to be measured in seconds, hundreds of milliseconds, and tens of milliseconds (in

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inspection time tasks, this refers to the stimulus duration rather than the response time). Therefore, at least in their items' timings and phenomenology, tests of processing speed are heterogeneous. The Cattell-Horn-Carroll, three-stratum model of psychometric intelligence incorporates, at the second level—below and less general than *g* (general intelligence) and above and more general than specific cognitive capabilities—a “broad cognitive speediness” factor, named 2S (Carroll, 1993, p. 625). Whereas Carroll (1993) stated that this capability, “is involved in any task or performance that requires rapid processing of information,” he also described possible “subvarieties” of 2S, i.e. 2 T and 2P which are, respectively, involved in the decision-making and response aspects of reaction-time tasks. Of course, discovering the covariance structure of the many speeded psychometric and experimental tasks is an ongoing research effort which can check and update Carroll's (1993) suggestions.

The second difficulty is that, when a task of processing speed correlates with individual differences in a test of higher or more complex cognitive capability or age-related changes in such a cognitive capability, it might be tempting prematurely to infer that processing speed causes/explains the latter's differences. However, the differences cannot be explained (even if some variance has been accounted for) if one does not have some mechanistic understanding (cf. Schubert, Hagemann, Löffler, & Frischkorn, 2020; cf. also Madole & Harden, 2022 who discuss causal inference and the differences between ‘variance accounted for’ and mechanistic explanation in another setting) of the processing speed variable that is the explanans.

It is interesting and non-trivial that scores on tests such as the Digit Symbol from the Wechsler Adult Intelligence Scale (Wechsler, 1998a) can account for much of the age-related variance in more complex-seeming cognitive tests (e.g., Salthouse, 1993). The same applies to four-choice reaction time's moderately-sized correlation with scores on complex cognitive tests (Der & Deary, 2017). However, in the present study we shall use inspection time as a procedure to assess processing speed (Vickers, Nettelbeck, & Willson, 1972; Vickers & Smith, 1986). Individual differences in this arguably-simpler processing speed task have replicated associations with higher cognitive ability (Grudnik & Kranzler, 2001) and its age-related changes (Deary, Johnson, & Starr, 2010; Gregory, Nettelbeck, Howard, & Wilson, 2008); therefore, it might have relatively good prospects for providing some causal understanding. Such understanding would ideally be based in terms of the brain processes that underpin the differences of interest. Inspection time is a psychophysical task (see Deary et al., 2004, for a description and illustration of the inspection time test used in the present study). In it, the participant has, on each trial, to indicate which of two vertical lines of markedly-different lengths is longer. The presentation time of the stimulus ranges from a few to over one hundred milliseconds, followed by a visual mask. There is a lawful association between stimulus duration and correctness of the response. There is no speeded response; participants are encouraged not to hurry in their responses. Phenomenologically, then, all that an inspection time test involves, on each of its trials, is a two-alternative stimulus appearing briefly followed by a leisurely forced response to indicate whether the right or left vertical line was longer.

The value of inspection time for understanding individual differences in age-related cognitive changes lies in how well it is understood, i.e. on its nomological network. Inspection time as a task was developed from a theory of perception in which the rate of intake of visual information showed differences between individuals (Vickers et al., 1972; Vickers & Smith, 1986). Scores on the inspection time task correlate modestly (from around 0.2 to sometimes above 0.3) with scores on more complex cognitive tests (Deary et al., 2010; Grudnik & Kranzler, 2001). Inspection time test scores are moderately to highly stable over time (Ritchie, Tucker-Drob, & Deary, 2014) and have moderate heritability (Edmonds et al., 2008; Luciano et al., 2005). Performing the inspection time task has a signature on fMRI brain imaging (Deary et al., 2004). In developmental and ageing studies, there is some evidence from cross-lagged panel-type designs that changes in inspection time might precede changes in higher cognitive functions (Deary, 1995; Ritchie et al., 2014), though such evidence is far from definitive for adducing a causal effect (Luciano et al., 2005).

The present study aims to add to what is known about inspection time (qua test of processing speed) as one route to understanding some of the individual differences in cognitive ageing. The main question being asked in this pre-registered study (https://osf.io/vuwzm/) is: what is the correlation between the slope of inspection time from age 70 to age 82 and the same-period slopes of general cognitive ability, memory, visuospatial reasoning, processing speed, and crystallised cognitive ability? Changes to the pre-registration plans are listed at the beginning of the Supplementary Materials. The participants were members of the Lothian Birth Cohort 1936 (Deary et al., 2007). The aspects of the study that add value are as follows. The sample is moderately large. The participants have a narrow range of ages, and so the within-person ageing differences occur in the setting small between-subject age differences. The participants took the same tests in the same location on five waves, between the mean ages of 70 and 82, a life-course period during which there is substantial mean decline in some cognitive domains, including processing speed, reasoning, and memory (Salthouse, 2010). The participants took a large battery of varied and well-validated cognitive tests. The participants were all community-dwelling and not suffering from acute illness.

2. Method

2.1. Participants

The Lothian Birth Cohort 1936 (LBC1936) is a narrow-age, longitudinal study of healthy cognitive ageing. Information regarding the background, recruitment and testing of LBC1936 participants is provided by Deary et al. (2007); Deary, Gow, Pattie, and Starr (2012)) and Taylor, Pattie, and Deary (2018). Participants were born in 1936 and recruited from the Edinburgh and Lothians areas of Scotland. Every three years, since about age 70, participants have completed a detailed medical history, and biomedical, physical, psycho-social, and cognitive assessments including a core battery of cognitive tests. The present study uses cognitive and other data collected during Wave 1 (2004–2007, N = 1091, age mean [M] = 70); Wave 2 (2007–2010, N = 866, age M = 73); Wave 3 (2011–2013, N = 697, age M = 76); Wave 4 (2014–2017, N = 550 age M = 79); and Wave 5 (2017–2019, N = 431, age M = 82). At each wave, cognitive and other assessments were completed in the Wellcome Trust Clinical Research Facility at the Western General Hospital, Edinburgh. Ethical approval was obtained from the Multi-Centre Ethics Committee for Scotland (MREC/01/0/56) and Lothian Research Ethics Committee (LREC/2003/2/29). All participants provided written informed consent. All 1091 LBC1936 participants were included in the analytical sample.

2.2. Measures

Participants completed the same battery of 13 cognitive tests at each wave of assessment. The battery included a test of inspection time which, in this report, is considered separately from the other cognitive tests as a possible correlate of their intercepts and age-related slopes.

2.2.1. Inspection time

This is a two-alternative, forced-choice procedure (the test used here is described in Deary et al., 2004). Participants were required to identify the longer of two parallel, vertical lines presented on a computer monitor for a variety of durations (15 durations ranging between 6 ms and 200 ms). In total, participants completed 150 trials (10 at each duration). Durations appeared at random. We used this method of constant stimuli, even though it took longer than an adaptive staircase procedure, so that we would have available a psychometric function for each person's inspection time performance. Each trial started with a visual cue followed by the stimulus (the two vertical lines) which was followed by a backward mask. After mask offset, participants could indicate which line (left or right) was longer. Participants were instructed to prioritise the accuracy of their responses and to take as long as they needed to respond on each trial; response time was not considered. The inspection time variable used in the present analysis was calculated as the total number of correct responses (maximum = 150). Participants were given training and practice items before each occasion on which they took the test and the test was not begun until the tester was satisfied that the participant was able to perform the task.

The remaining cognitive tests can be grouped according to four cognitive domains, as has been demonstrated in this sample empirically (Tucker-Drob, Briley, Starr, & Deary, 2014): visuospatial reasoning, processing speed, memory, and crystallised ability. In appearance, two of the cognitive tests might seem unusual in their allocation to a cognitive domain, i.e. Digit Span backwards to memory, and phonemic fluency to crystallised ability. However, this followed their empirical associations with the tests in the battery and they have strong loadings, respectively, on the memory and crystallised ability factors, as illustrated in Fig. 3 A of Ritchie et al. (2016).

2.2.2. Visuospatial reasoning

This was assessed by the Matrix Reasoning and Block Design subtests from the Wechsler Adult Intelligence Scale, 3rd UK Edition (Wechsler, 1998a) and the Spatial Span (Forward and Backward) subtest from the Wechsler Memory Scale, 3rd UK Edition (Wechsler, 1998b),

2.2.3. Processing speed

This was assessed by the Symbol Search and Digit Symbol tests from the Wechsler Adult Intelligence Scale, 3rd UK Edition (Wechsler, 1998a), and a four-choice reaction time test (the same test as described in Der & Deary, 2017).

2.2.4. Memory

This was assessed by the Digit Span Backward subtest from the Wechsler Adult Intelligence Scale, 3rd UK Edition (Wechsler, 1998a), and the Verbal Paired Associates and Logical Memory subtests from the Wechsler Memory Scale, 3rd UK Edition (Wechsler, 1998b).

2.2.5. Crystallised cognitive ability

This was assessed by the National Adult Reading Test (NART; Nelson & Willison, 1991), the Wechsler Test of Adult Reading (WTAR; Holdnack, 2001), and a test of phonemic verbal fluency using the letters C, F, and L (Lezak, Howieson, Loring, & Fischer, 2004).

2.2.6. Mini-mental state examination (MMSE)

The MMSE (Folstein, Folstein, & McHugh, 1975) was tested at all waves. It is often used as an indicator of possible cognitive pathology. Here, it was used in sensitivity analyses in which a cut-off score of 24 was used, as described below.

2.2.7. Other variables

Some other variables were included as covariates. Covariate variables were age in days at the time of testing, sex, and visual acuity. Visual acuity was indexed by corrected visual acuity in the better-seeing eye. At each wave of the study, visual acuity was assessed by a trained research nurse using a Snellen chart. For the analysis, the Snellen fraction was converted to logMAR (logarithm of the minimum angle of resolution). Partially completed lines were handled by rounding down to the previous line if more than half of the letters were missed, or rounding up to the next line if half or more than half of the letters were identified on that line.

2.3. Main analyses

The R software environment version 4.1.3 (R Core Team, 2022) was used for data preparation and for creating descriptive tables and plots. All other analyses were carried out using Mplus Version 8.6 (Muthén & Muthén, 2017).

We calculated the means and standard deviations of all the cognitive tests followed by correlations among inspection time and the other cognitive tests. These descriptive statistics are presented for all five waves of cognitive testing for all participants and, separately, for only those participants who completed all five waves of cognitive testing (completers).

Levels (intercept at age 70) and slopes (representing change in cognitive test performance across the 12 years from age 70 to age 82) were estimated using growth curve models (Duncan & Duncan, 2004; McArdle, 1988). The linear slopes were estimated using the average time lag between waves 1–2 (2.98 years), 1–3 (6.75 years), 1–4 (9.82 years), and 1–5 (12.54 years) as factor loadings, with the initial loading from the test score at wave 1 to the slope factor set to zero.

Next, we applied a factor-of-curves model (McArdle, 1988) to estimate levels and slopes of each of the cognitive ability domains (visuospatial reasoning, processing speed, memory, and crystallised ability). For each cognitive domain model, the levels and slopes of three cognitive tests (assessing that domain) were treated as indicators of higher-order factors representing the cognitive ability domain level and slope. Factors were identified using the marker variable method (setting the loading of the first indicator to 1).

To examine the correlation between the intercepts and slopes of inspection time and the cognitive domains, we ran models that estimated the intercept and slope of inspection time and the intercept and slope of each cognitive domain in turn. These models were adjusted for sex, age, and visual acuity. Sex was treated as a time-invariant covariate. Visual acuity was recorded at each wave of assessment and treated as a time-varying covariate. Inspection time and the cognitive domains' intercepts and slopes were regressed on sex. The individual cognitive tests and inspection time scores were regressed on scaled ($M = 0$, $SD = 1$) age at each time of testing. Age in days had been recorded at each wave of cognitive testing. For the analysis, each cognitive test score was regressed on scaled age at the time of testing (e.g., Wave 1 cognitive tests scores were regressed on scaled age at Wave 1). Scaled age was included as a time-dependent covariate in order to minimise the effect of any within-wave age differences on cognitive performance while still capturing age-related changes in performance across waves. Inspection time scores were additionally regressed on visual acuity at the time of testing.

In each of the cognitive domain models, described above, some of the cognitive tests' slopes had residual variances that were close to zero and estimated as negative. This can occur when most of the test's slope variance is shared with the variance of the higher-order slope factor. It is important that models converge on within-bounds estimates, without any negative residual variance (which would mean that >100% of the test variance contributes to latent factor estimates). To ensure this, the residual variance of the following cognitive test slopes were fixed at zero: WTAR, Logical Memory, and Spatial Span.

Next, we estimated the correlation between the intercepts and slopes of inspection time and general cognitive ability. General cognitive ability was estimated by including all four cognitive domain models and estimating higher-order factors representing general cognitive ability level (indicated by the four cognitive domain levels) and general cognitive ability slope (indicated by the four cognitive domain slopes). Fig. 1 provides an illustration of this model. As described above, the model included the covariates sex, age, and visual acuity. The residual variances of the NART and Symbol Search test slopes were additionally fixed at zero in this model.

In a second iteration of the model described above, we estimated the correlation between the intercepts and slopes of inspection time, general cognitive ability and, simultaneously, the cognitive domains. Associations with the intercepts and slopes of the cognitive domains were specified for each domain in turn (allowing associations with all four

Fig. 1. Diagram of the main analysis.
Ellipses represent latent variables, rectangles observed variables, double headed arrows correlations, and single headed arrows regressions/factor loadings. Crystal = Crystallised ability, Vis = visuospatial reasoning, speed = processing speed, G = general cognitive ability. Each cognitive domain was estimated using three cognitive tests.

domains in the same model resulted in non-convergence). These models did not include the covariates (age, sex, and visual acuity) as including them also resulted in convergence issues.

All models were run with the Maximum Likelihood (ML) estimator. Participants remaining in the study at Wave 5 tend to have better physical and cognitive health than those who leave (Taylor et al., 2018). To minimise bias due to this pattern of attrition, we took account of all available data using the Full Information Maximum Likelihood (FIML) algorithm. This assumes that data are missing at random.

Model fit was assessed using the comparative fit index (CFI), Tucker–Lewis index (TLI), and root-mean-square error of approximation (RMSEA). CFI and TLI $\geq$ 0.90, and RMSEA $\leq$0.08 were considered to indicate acceptable fit (Little, 2013).

2.4. Sensitivity analyses

Firstly, we ran additional analyses to check whether the main results might be unduly affected by the small number of participants with possible pathological cognitive decline. Therefore, the main analyses, testing associations between intercepts and slopes of inspection time and the cognitive domains and general cognitive ability, were re-run excluding participants with a MMSE score of <24 at any wave of testing (those who attended but did not complete the MMSE were also excluded).

Secondly, we ran additional analyses to check whether cognitive domains would be represented better by using a single test rather than a latent trait derived from a few tests. Therefore, the main analyses were repeated, replacing the cognitive domain levels and slopes with those of an individual cognitive test, used to represent that domain. For each model, we selected the highest-loading test for that domain. These were the WTAR (for crystallised ability), Logical Memory (for memory), Symbol Search (for processing speed), and Matrix Reasoning (for visuospatial reasoning).

Thirdly, we ran additional analyses to examine whether a non-linear model of inspection time change would be better than a model which assumed linear changes. Therefore, we examined the trajectory of change in inspection time by comparing models that specified linear change (as in the models described above) to: i) a model specifying quadratic change in inspection time; and ii) a model that allowed the trajectory of inspection time change to be freely estimated. This latter approach involved freeing the factor loadings for waves 3–5 and allowing the shape of the growth curve to be determined by the data. The factor loadings for waves 1 and 2 were fixed at 0 and 1, respectively. As reported in the Results section, the freely-estimated model of inspection time provided a slightly better fit to the data, relative to the linear and quadratic models. We therefore re-ran the main analysis,

Table 1
Cognitive test scores at waves 1–5 (N = 1091).

	Wave 1	Wave 2	Wave 3	Wave 4	Wave 5
Matrix Reasoning					
N	1086	863	689	535	418
Mean (SD)	13.49 (5.13)	13.17 (4.96)	13.04 (4.91)	12.90 (5.03)	12.93 (5.22)
Block Design					
N	1085	864	691	535	420
Mean (SD)	33.79 (10.32)	33.64 (10.08)	32.18 (9.95)	31.20 (9.63)	29.90 (9.60)
Spatial Span					
N	1084	861	690	536	421
Mean (SD)	7.36 (1.42)	7.35 (1.38)	7.31 (1.36)	7.07 (1.36)	6.95 (1.43)
Logical Memory					
N	1087	864	688	542	421
Mean (SD)	71.46 (17.96)	74.30 (17.88)	74.58 (19.20)	72.71 (20.39)	72.15 (21.52)
Verbal Pairs					
N	1050	843	663	497	380
Mean (SD)	26.44 (9.13)	27.18 (9.46)	26.41 (9.56)	27.14 (9.55)	27.37 (9.54)
Digit Backwards					
N	1090	866	695	548	426
Mean (SD)	7.73 (2.26)	7.81 (2.29)	7.77 (2.37)	7.56 (2.18)	7.19 (2.33)
Verbal fluency					
N	1087	865	696	547	426
Mean (SD)	42.42 (12.54)	43.18 (12.94)	42.90 (12.76)	43.61 (13.33)	43.55 (12.69)
NART					
N	1089	864	695	546	426
Mean (SD)	34.48 (8.15)	34.38 (8.18)	35.02 (8.03)	35.59 (8.19)	36.05 (7.81)
WTAR					
N	1089	864	694	546	426
Mean (SD)	41.02 (7.17)	41.01 (6.97)	41.09 (7.02)	41.63 (7.03)	42.19 (6.61)
Digit Symbol					
N	1086	862	685	535	418
Mean (SD)	56.60 (12.93)	56.40 (12.31)	53.81 (12.93)	51.24 (13.01)	50.98 (12.79)
Symbol Search					
N	1086	862	687	529	415
Mean (SD)	24.71 (6.39)	24.61 (6.18)	24.60 (6.46)	22.68 (6.72)	22.21 (6.93)
Choice reaction time					
N	1084	865	685	543	423
Mean (SD)	0.64 (0.09)	0.65 (0.09)	0.68 (0.10)	0.71 (0.11)	0.72 (0.12)
Inspection time					
N	1041	838	654	465	382
Mean (SD)	112.14 (11.00)	111.22 (11.79)	110.14 (12.55)	106.96 (13.60)	106.03 (12.72)

A higher choice reaction time score indicates a slower reaction time.

Table 2
Cognitive test scores for completers at waves 1–5 (N = 289).

	Wave 1	Wave 2	Wave 3	Wave 4	Wave 5
Matrix Reasoning					
Mean (SD)	15.17 (4.84)	14.66 (4.79)	14.30 (4.55)	13.95 (4.81)	13.66 (5.03)
Block Design					
Mean (SD)	36.69 (9.77)	36.59 (10.18)	34.66 (9.50)	33.17 (9.32)	31.11 (9.02)
Spatial Span					
Mean (SD)	7.67 (1.37)	7.63 (1.30)	7.61 (1.29)	7.27 (1.28)	7.12 (1.30)
Logical Memory					
Mean (SD)	76.27 (16.81)	79.87 (15.10)	79.61 (15.18)	78.77 (15.44)	76.13 (18.19)
Verbal Pairs					
Mean (SD)	29.03 (7.94)	30.67 (7.38)	29.27 (8.12)	29.09 (8.41)	27.90 (9.01)
Digit Backwards					
Mean (SD)	8.31 (2.27)	8.38 (2.30)	8.26 (2.43)	7.87 (2.18)	7.40 (2.22)
Verbal fluency					
Mean (SD)	44.62 (12.16)	45.53 (11.80)	45.42 (12.01)	46.08 (11.97)	44.78 (12.20)
NART					
Mean (SD)	36.54 (7.45)	36.12 (7.42)	36.71 (7.29)	36.86 (7.63)	36.96 (7.53)
WTAR					
Mean (SD)	43.10 (6.19)	42.80 (6.00)	42.64 (6.13)	42.94 (6.25)	43.13 (6.09)
Digit Symbol					
Mean (SD)	60.73 (11.43)	60.76 (11.01)	58.11 (11.03)	54.75 (11.06)	52.50 (11.57)
Symbol Search					
Mean (SD)	26.56 (6.43)	26.66 (5.10)	26.76 (5.62)	24.42 (5.66)	23.27 (6.20)
Choice reaction time					
Mean (SD)	0.62 (0.07)	0.62 (0.07)	0.65 (0.08)	0.68 (0.09)	0.71 (0.11)
Inspection time					
Mean (SD)	114.24 (10.20)	113.74 (10.55)	112.49 (11.16)	109.79 (11.34)	106.82 (11.53)

A higher choice reaction time score indicates a slower reaction time.

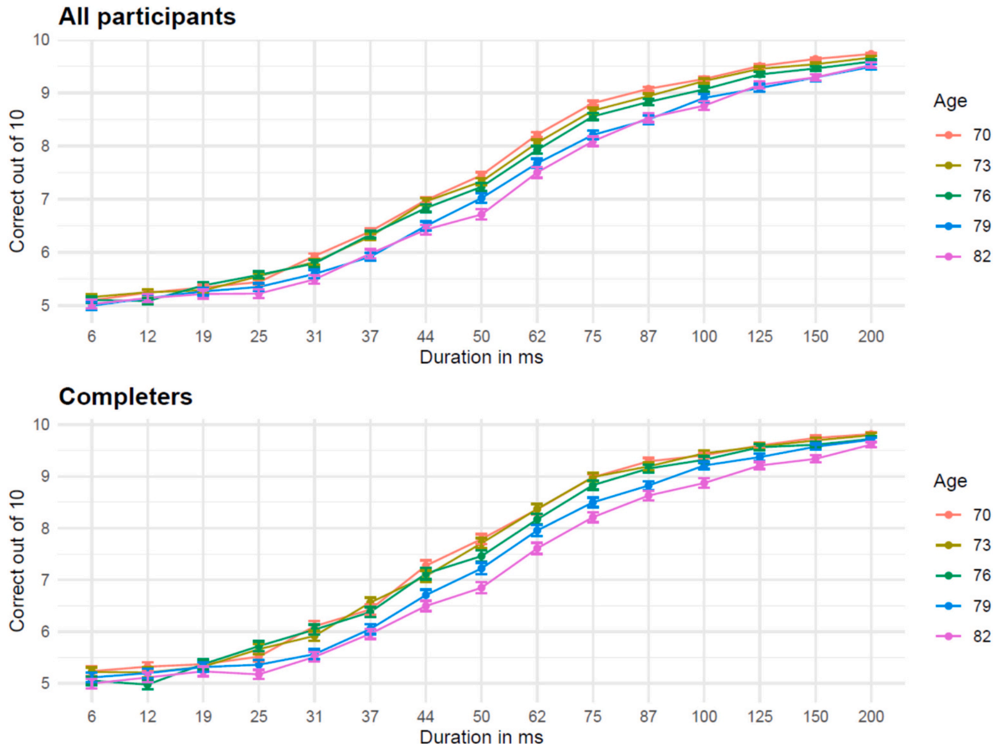

Fig. 2. Mean number of correct responses per stimulus duration in the inspection time test across waves 1–5.
The figures show means and standard errors for the number of correct responses per stimulus duration in the inspection time test. The colour coding indicates the wave of assessment (see legend). Completers = participants who completed all five waves of cognitive testing.

Table 3
Covariate variables at waves 1–5.

	Wave 1	Wave 2	Wave 3	Wave 4	Wave 5
Age					
N	1091	866	697	550	431
Mean (SD)	69.54 (0.83)	72.50 (0.71)	76.25 (0.68)	79.33 (0.62)	82.01 (0.47)
Sex					
Male	548 (50.2%)	448 (51.7%)	360 (51.6%)	275 (50.0%)	209 (48.5%)
Female	543 (49.8%)	418 (48.3%)	337 (48.4%)	275 (50.0%)	222 (51.5%)
Corrected visual acuity					
N	765	594	484	393	288
Mean (SD)	0.03 (0.12)	0.08 (0.13)	0.14 (0.15)	0.16 (0.17)	0.17 (0.14)

Visual acuity = corrected acuity in the better seeing eye in logMAR units.

replacing the linear model of inspection time with a freely-estimated one.

Fourthly, we ran analyses excluding participants who achieved <17 items correct out of 20 for the combined two longest durations of the inspection time trials (150 ms and 200 ms). This was done to check that participants had retained their attention throughout the task (stimulus durations were randomised and therefore longer durations could appear at any point in the test).

3. Results

3.1. Descriptive results

The means and standard deviations for all subjects for all cognitive tests, including inspection time, are shown in Table 1. The Ns with available data at Wave 1 range from 1041 to 1090. The Ns at Wave 5 range from 382 to 426. The means and standard deviations for those subjects (completers) who completed all five waves of cognitive testing and provided full data on all tests are shown in Table 2; the N is 289. Comparing Wave 1 with Wave 5 only, inspection time performance declined across the 12 years of the study. Based on data from all subjects (Table 1), the decline was about half of a standard deviation; based on completers only (Table 2), the decline was about two thirds of a standard deviation. The change in inspection time by age is illustrated in more detail in Fig. 2 which shows, for all subjects and for completers only, how the mean number of correct responses for each stimulus duration changed from age 70 to age 82. There is a steady mean decline for those durations that are neither near to chance responding nor close to perfect responding. The pattern for the other 12 cognitive tests is that the means of the processing speed and visuospatial reasoning tests tend to decline over the waves (Tables 1 and 2). The crystallised ability tests tend not to decline in mean scores. Logical Memory and Verbal Pairs tend not to decline. Summary statistics for age, sex, and corrected visual acuity are shown in Table 3. The descriptives of the cognitive test scores in the sample across this period have been plotted by Corley et al. (2023).

For descriptive purposes, the correlations among inspection time and other cognitive tests are shown in Supplementary Tables 1 to 5 for all subjects, and in Supplementary Tables 6 to 10 for those who completed all cognitive tests on all five waves. With respect to inspection time's correlations with other cognitive tests, the highest of the correlations tend to be with tests of processing speed (from 0.18 to 0.45 in completers across the five waves); next comes tests of visuospatial reasoning (0.09

Table 4
Summary results for the association between inspection time, the cognitive domains and general cognitive ability.

Variables	r	95% CI	p
Intercept associations			
Inspection time ↔ Crystallised	0.243	0.17, 0.317	<0.001
Inspection time ↔ Memory	0.312	0.226, 0.399	<0.001
Inspection time ↔ Speed	0.613	0.549, 0.678	<0.001
Inspection time ↔ Visuospatial	0.462	0.388, 0.536	<0.001
Inspection time ↔ g	0.536	0.466, 0.607	<0.001
Inspection time ↔ g*	0.402	0.324, 0.479	<0.001
Slope associations			
Inspection time ↔ Crystallised	0.459	0.162, 0.756	0.002
Inspection time ↔ Memory	0.709	0.536, 0.881	<0.001
Inspection time ↔ Speed	0.857	0.689, 1.025	<0.001
Inspection time ↔ Visuospatial	0.697	0.446, 0.947	<0.001
Inspection time ↔ g	0.898	0.752, 1.044	<0.001
Inspection time ↔ g*	0.861	0.688, 1.035	<0.001

Models controlled for age, sex, and visual acuity. CI = confidence interval.
* g = estimated excluding the processing speed domain.

to 0.33), followed by lower correlations with tests of memory (−0.04 to 0.21) and crystallised ability (0.02 to 0.26). The correlations among all the non-inspection time tests were universally in the direction indicating that people who did well on one test tended to do well in all the others (note that directions of correlations are reversed for choice reaction time because a higher score indicates slower reactions).

Standardised path weights for the cognitive domains on general cognitive ability level and slope are shown in Fig. 1; they are also displayed in Supplementary Table 11 along with standardised path weights for the individual cognitive tests on the cognitive domains' levels and slopes. The means and variances of the four cognitive domains' levels and slopes across the five waves (about 12 years) of testing are shown in Supplementary Table 12. Participants aged from a mean of about 70 in Wave 1 to 82 in Wave 5. Over that period, the decline (indicated by a minus sign) in each of the four cognitive domains, expressed as standard deviation units per year, was as follows: processing speed = −0.089; visuospatial reasoning = −0.062; memory = −0.027; crystallised ability = −0.014 (Supplementary Table 12). The means and variances of the individual cognitive tests' levels and slopes across the five waves are shown in Supplementary Table 13.

3.2. Modelling results

All coefficients are $p < 0.001$ unless stated otherwise. All of the coefficients reported below are standardised associations estimated from the model.

3.2.1. Change in inspection time versus change in each of the four cognitive domains

Models were estimated for changes in inspection time and, singly, each of the four cognitive domains across the 12 years (five waves of data) of the study. Levels and slopes of the four cognitive domains were modelled from the levels and slopes of the 12 individual cognitive tests (Fig. 1). Sex, age, and visual acuity (the latter two were time-varying) were included as covariates. The range of fit statistics for the models were CFI = 0.983 to 0.948; TLI = 0.981 to 0.942 and RMSEA = 0.037 to 0.019. Summary results are shown in Table 4 and more detailed results in Supplementary Tables 14 to 17. The associations between inspection time intercept and the intercepts of each of the four cognitive domains were as follows: crystallised ability = 0.243; memory = 0.312; processing speed = 0.613; visuospatial reasoning = 0.462. The associations between inspection time slope and the slopes of each of the four cognitive domains were as follows: crystallised ability = 0.459 (p = 0.002); memory = 0.709; processing speed = 0.857; visuospatial reasoning = 0.697. The various intercept-slope associations are shown in the Supplementary Tables 14–17.

3.2.2. Change in inspection time versus change in general cognitive ability

General cognitive ability level (intercept) and slope (trajectory) were modelled using the five waves of data (12 years) from the levels and slopes of the four cognitive domains which were modelled from the levels and slopes of the 12 individual cognitive tests (Fig. 1). Sex, age, and visual acuity (the latter two were time-varying) were included as covariates. The fit statistics for the model were CFI = 0.945; TLI = 0.943; RMSEA = 0.029. The intercepts of inspection time and general cognitive ability correlated at 0.536. Inspection time and general cognitive ability slopes correlated at 0.898 (Table 4, Supplementary Table 18). There were similar associations (just below 0.2) between the intercept of inspection time and the slope of general cognitive ability and vice versa.

Additional analyses were run in which models contained associations between the levels and slopes of inspection time and general cognitive ability and also, one at a time, the levels and slopes of each of the four cognitive domains. The results are shown in Supplementary Tables 19 to 22. The interest here was in whether the slope of inspection time would associate with the slope of a cognitive domain after taking into account that cognitive domain's association with general cognitive ability. The results were mostly null, though there was an association of 0.199 (p = 0.030) between the slopes of inspection time and memory (i.e. the residual variation in memory after taking into account memory's association with general cognitive ability).

3.3. Sensitivity analyses

Additional analyses were run excluding 48 participants whose Mini-Mental State Examination (MMSE) score was <24 at any wave of testing, or who did attend but did not provide a MMSE score. The results (Supplementary Tables 23 to 27) were very similar to the main analyses already reported.

Additional analyses were run to repeat the inspection time-cognitive domain analyses; however, in these additional analyses, only the highest-loading cognitive test was used to represent each domain. The results are reported in Supplementary Tables 28 to 31. The associations between inspection time intercept and the intercepts of each of the four cognitive domains' highest-loading tests were as follows: Wechsler Test of Adult Reading (crystallised ability) = 0.241; Logical Memory (memory) = 0.199; Symbol Search (processing speed) = 0.538; Matrix Reasoning (visuospatial reasoning) = 0.341. The associations between inspection time slope and the slopes of each of the four cognitive domains were as follows: Wechsler Test of Adult Reading = 0.161 (p = 0.37); Logical Memory = 0.694; Symbol Search = 0.868; Matrix Reasoning = 0.640. These associations tend to be a little lower than those with the cognitive domains formed as latent traits from three tests, but with only the inspection time-crystallised association reducing to non-significance. The various intercept-slope associations are shown in Supplementary Tables 28 to 31.

Further analyses examined whether the main results would be different if a non-linear model had been applied to inspection time changes with age. The above-described results used a linear model of inspection time changes across the five waves of the study (age 70 to 82). The measurement model that fitted best for inspection time across this period allowed the slope of inspection time to be freely estimated (Supplementary Table 32), although its fit statistics (CFI = 0.992; TLI = 0.989; RMSEA = 0.035) were similar to those of the quadratic model (CFI = 0.993; TLI = 0.988; RMSEA = 0.036). Comparative fit indices (BIC and AIC) are shown in Supplementary Table 32. The freely estimated model was chosen based on the lower BIC for this model. The freely-estimated factor loadings indicated that decline in inspection time performance was accelerating, particularly at Waves 4 and 5 (the freely estimated factor loadings for Waves 3, 4 and 5 were 2.098, 4.866 and 6.360, respectively). Supplementary tables 33 to 36 show results from additional sensitivity analyses in which the slope of inspection time was allowed to be estimated freely (i.e., freeing factor loadings for Waves 4 and 5). The coefficients of association between inspection time (intercept and slope) and the cognitive domains (intercept and slope) were similar to those in the main analyses which specified a linear slope for inspection time.

The final analyses omitted 153 participants who scored <17 out of 20 in the combined two longest stimulus durations in the inspection time test. The sample size for this analysis was 938 (including those with missing data on inspection time). The results are shown in Supplementary Tables 37–40. The results are similar to the analyses in which these participants are included (Table 4) but with several associations being slightly smaller.

4. Discussion

The main result from the present analyses was the large association between individual differences in 12-year change (there was a mean decline) in inspection time and those in general cognitive function between age 70 and 82 in community-dwelling people. There were strong associations, too, between the 12-year changes in inspection time and the cognitive domains of memory, processing speed, visuospatial reasoning, and crystallised ability, but these associations were mostly accounted for by the domains' having shared (general cognitive ability) slope variance. After the association between changes in inspection time and changes in general cognitive functioning were taken into account there was a small additional association between changes in inspection time and changes in memory, but that result was marginal, statistically, and might have been a type 1 error.

The finding that changes in inspection time and general cognitive ability are highly correlated from age 70 to 82 expands on previous findings. A previous report that used waves 1, 2, and 3 on the same sample that was studied here found an association of 0.78 between age 70 and 76 (Ritchie et al., 2014). The slightly higher association reported here might be because the twice-as-long duration—taking the subjects into older age during which there was greater mean decline—afforded a more reliable estimate of changes in the inspection time and other cognitive tests. What we report here is a correlation between, on average, worsening of inspection time and general cognitive ability; we note that there is evidence that inspection time and other cognitive functions also correlate across development in children, where both are improving on average (Edmonds et al., 2008).

Finding that age-related changes in inspection time and general cognitive ability are highly correlated is consistent with, but does not necessarily mean that, the slowing of processing speed is a cause of decline in higher cognitive capabilities (Luciano et al., 2005). There is a large amount of evidence that tests of processing speed and higher cognitive abilities are associated, especially in older age (Deary et al., 2010; Salthouse, 1993; Tucker-Drob, Brandmaier, & Lindenberger, 2019). However, three possibilities remain for this association, i.e., that: the slowing of processing speed is one cause of general cognitive ageing; that the decline in general cognitive ability slows speed of processing; or that some third set of factors contributes both to age-related decline in general cognitive ability and to processing speed, including inspection time. We address these in turn.

4.1. Inspection time as 'basic'

It might be argued that the theory behind the inspection time measure—that it indexes a fundamental limitation of visual information processing—and evidence for its biological underpinnings support the possibility that inspection time assesses an individual difference that is causal to differences in age-related changes in higher cognitive abilities. However, not-yet enough has been done to validate the theory or tie it to brain functioning. One lead to date has been that individual differences in the health of the brain's white matter (the connecting fibres) are related to higher cognitive capabilities in older age, perhaps mediated via processing speed (Fuhrmann, Simpson-Kent, Bathelt, The CALM Team, & Kievit, 2020; McCormick & Kievit, 2023; Penke et al., 2010; Penke et al., 2012). There are few other biological studies. Inspection time's fMRI signature was explored by Deary et al. (2004). Their analysis of the brain's blood oxygenation level-dependent (BOLD) response while performing essentially the same inspection that that was used in the present study found, "that the difficulty of the visual discrimination [i.e. shorter stimulus exposure durations] was related to bilateral activation in the inferior fronto-opercular cortex, superior/medial frontal gyrus, and anterior cingulate gyrus, and bilateral deactivation in the posterior cingulate gyrus and precuneus" (Deary et al., 2004). Further examination found that activation was more closely related to the harder/briefer stimuli but that deactivation occurred with all difficulty levels of the stimulus. Functional connectivity analysis suggested two networks: a frontal network, "possibly associated with processing of visually degraded percepts"; and a posterior network that, "might subserve processing of a visual discrimination task that has high processing demands and combines several fundamental cognitive domains." More functional brain imaging studies would be useful, especially regarding individual differences, although that could still leave undecided whether any associations were causal to or a result of differences in inspection time performance. Another biological route to studying inspection time is via psychopharmacological intervention. In one such study it was found that controlled acute hypoglycaemia impaired inspection time performance by about one standard deviation, although the result is not specific because this intervention caused decrements in other visual processing tasks, in other processing speed tasks, in other cognitive domains, and in general fluid cognitive ability (McCrimmon, Deary, Huntly, MacLeod, & Frier, 1996).

4.2. Inspection time as 'higher-level'

Secondly, there is little evidence for the opposite direction of causation, i.e. that generally smarter people find some way(s) to obtain better inspection time scores. This is related to the issue of whether inspection time differences are largely based on lower-level processing limitations or due to higher-level capabilities. That is, it may not be assumed that the original theory of inspection time—that it articulates a limitation in perceptual apprehension—is either correct or that it applies to all or any of the operationalisations of inspection time (theory) as inspection time tasks. Some ideas concerning 'top down' rather than 'bottom up' (i.e. perceptual-apprehension limitation) explanations have been tested. Possible strategies in performing the inspection time task have been explored (Simpson & Deary, 1997; Stough, Bates, Mangan, & Colrain, 2001) and were discussed (Deary & Stough, 1996; Simpson & Deary, 1997) with the conclusions that: strategies probably do not create but might disrupt the inspection time-intelligence correlation; reported strategy formation did not improve inspection time performance; feedback during the inspection time task (there is normally no feedback about correct and wrong responses) does not enhance strategy use or performance on an inspection time tasks; that better backward masks (such as the one used in the present study) can prevent the use of strategies (e.g. movement artefacts at stimulus offset); and that strategy reporting might sometimes be a verbal epiphenomenon. Another 'top-down' concern is whether aspects of attention are related to inspection time performance. Although some have suggested that this might be the case (Bors, Stokes, Forrin, & Hodder, 1999)—based on the finding that those with lower cognitive test scores make more errors on the easiest (longest) stimulus durations—we have found that, with the present cohort and task (which uses the method of constant stimuli specifically to check that there is not inattentiveness during the task), almost all participants perform highly throughout at the easier durations. The role of attentional control has been pursued further—using dual-task procedures—but it is hard to assess what this means for the origins of inspection time performance when, for example, the non-inspection time task in the dual-task procedure is instructed to be the 'primary' task to which participants should attend (Fox, Roring, & Mitchum, 2009). A study which employed simultaneous eye-tracking while an inspection time task was performed found: that it was important for participants to have sufficient instruction and practice trials on the task (as are included in the present study); that, when subjects were sufficiently familarised with the inspection time task, those who reported seeing visual illusions did not perform better or worse than those who did not; and that people were less likely to respond correctly if they blinked when the stimulus was presented (Eisma & de Winter, 2020). It is correct and useful that research continues—in parallel with the type of work conducted in the present study—to help us to understand what contributes to individual differences in inspection time (Nettelbeck, 2001).

4.3. Inspection time as one indicator of 'common cause'

The third possibility—that inspection time are correlated because they are part of more general cognitive ageing, and perhaps overall brain ageing, and perhaps even general bodily ageing—fits with some genetically-informed studies (Luciano et al., 2005) and with the idea of there being some general causes of many aspects of human ageing. This latter possibility is part of the set of ideas captured by the idea of a common cause of some ageing phenotypes (Kiely & Anstey, 2017). This idea can be formulated more or less generally; that is, perhaps inspection time and general cognitive ability changes have a common cause; more generally, perhaps the causes are shared in part with other brain functions such as sensory and motor processes; and more generally still, perhaps they are shared with other aspects of bodily ageing.

4.4. Other research directions

The fact that these three possibilities cannot yet be decided upon does not mean that the present findings represent no progress in the field. The findings are in a relatively large sample, over a long and relevant (for human ageing) period, and they are based on a large battery of well-validated cognitive tests. At their heart, the reported associations are surprising, i.e. that individual differences found in ageing-related changes in an apparently simple visual discrimination—which does not require participants to respond quickly—are related to individual differences in changes in complex cognitive tasks from different domains. It is worth digging away at the biological and social correlates of both sides of the correlation to understand it better.

Beyond concerns about the place of inspection time within ageing, it will be useful more generally to pursue other lines to understand the foundations of inspection time performance and its individual differences. This will include work in experimental/cognitive psychology and psychophysics. For example, a helpful study explored inspection time and related tasks and did not find that performance differences were based in oculomotor capability (Garaas & Pomplun, 2008).

Also valuable could be the work that is described as a 'neuro-cognitive-psychometrics' approach. It combines psychometric cognitive tests, processing speed tests, brain measures, and mathematical-componential modelling to try to discover the psychological components that account for speed-cognitive associations and their brain foundations (Schubert & Frischkorn, 2020). This might succeed where previous attempts to seek basic processes underlying speed and intelligence differences have failed or been inconclusive (Deary, 2000; Sternberg, 2022). Schubert et al. (2020) applied a diffusion model to extract performance parameters from participants' reaction times on the Sternberg memory task and the Posner letter-matching task. They also collected electroencephalographic (EEG) data during the performance of these tasks. From this combination of modelling and EEG-derived evoked response potential latencies they concluded that, "some of the covariance between age and fluid intelligence could be explained by individual differences in the speed of non-decisional processes such as encoding, memory retrieval, response preparation, and response execution." Because the inspection time procedure used here does not have a speeded response, perhaps there is agreement that encoding is one mediating source of individual differences between age and fluid cognitive capabilities. It is notable that Schubert et al. (2020) did not find a significant association between age and drift rate—the reaction time parameter that is thought to capture the speed of accumulation of evidence from a stimulus—because the theory of inspection time posited that the accumulation of information from a stimulus was collected in quanta and that the minimum quantal time showed individual differences (purported to be assessed by inspection time tests) that have subsequently been related to intelligence test scores and age. However, they did speculate that drift rate might increase beyond the age at which their sample stopped, i.e. at about 60, which is ten years younger than the baseline age of testing in the present sample. More evidence is needed to test that idea, which is extant following another study from the same research team (von Krause, Lerche, Schubert, & Voss, 2020). In that study they examined reaction time parameters from 18 tasks—i.e. faster and slower responded-to materials from three tests each with verbal, numerical, and figural stimulus characteristics. Again, this team found that non-decision parameters—those involving encoding and motor processes—associated with age, and speculated that this might be a sign that people become more cautious with older age (their oldest participant was 62). No single study can resolve these matters. It is far from straightforward to compare inspection time (in which the stimulus displays are manipulated with times mostly in the tens of milliseconds) with the Posner and Sternberg reaction time procedures which deliver response times that are much longer and which then are subjected to modelling to extract parameters (which have to be validated). If one were to attempt a triangulation between these reaction time studies and the present study then more focus on age-related changes in stimulus encoding as a mediator between age and cognitive capabilities might be warranted.

4.5. Limitations of the present study

The present study has limitations. The Lothian Birth Cohort 1936 is not fully representative of its background population, one outcome of which is that the associations found within it are sometimes slightly underestimated (Johnson, Corley, Starr, & Deary, 2011). The sample is drawn from a single year of birth and from a single geographical location, and this further limits the results' generalisability; this is also a strength, because it largely rules out between-subject age differences. Although it might be stated that having a visual processing task (inspection time) that lasts about 25 min within an already-large cognitive battery is unusual and quite valuable in an older-age sample, it should also be recognised that exploring the psychometric curve of each person's inspection time performance would ideally have been done at greater length and with larger numbers of subjects. The model of inspection time's age-related slope (linear, quadratic etc.) should ideally be tested in an independent sample. We note that freely estimating some of the parameters, as we did here in one model, is a nearer-to-saturated model and more likely to be over-fitted.

We cannot fully exclude the possibility that some part of the association found in the present study between inspection time slope and the slope of more complex cognitive performance was due to early cognitive pathology. We employed exclusion by low MMSE score to try to obviate this in sensitivity analyses. In our older Lothian Birth Cohort 1921 (LBC1921) we previously examined this issue in more detail. The LBC1921 participants had been studied for determinants of cognitive change between age 11 and age 79 in a number of studies. Across the next 16 years, they were ascertained for dementia diagnoses (Sibbett, Russ, Pattie, Starr, & Deary, 2018) and then the data from those studies was reanalysed. We found that taking into account subsequent dementia hardly altered the associations between the determinants and age 11-to-age 79 cognitive change. On the other hand, death within the next four years after age 79 (terminal decline) reduced most associations to non-significance.

We did not model retest effects in the cognitive tests used in the present study. This is because it has been found that latent slopes (ageing-related changes) in cognitive tests may be modelled adequately without including retest effects and it has been suggested that retest effects might lack sufficient individual differences to be modelled (Tucker-Drob, Johnson, & Jones, 2009). Whereas Tucker-Drob et al. (2009) found a large and significant correlation between the longitudinal slope of reasoning and processing speed, the association between retest effects for these two cognitive domains was non-significant. Of course, it is likely that, given that most cognitive tests have some retest/familiarity/practice effects, there is some underestimation of any absolute mean decline in performance—especially between the first and second waves—but that was not the outcome of interest here.

Attrition is an inescapable problem in longitudinal studies. It is plausible that missingness on the cognitive test scores could be related to participants' unobserved cognitive test scores, post drop-out. Previous investigation of dropout in the LBC1936 sample (with three waves of cognitive data) indicated that baseline covariates cannot fully account for patterns of attrition (Ritchie et al., 2016) and therefore the issue cannot be fully resolved by the inclusion of auxiliary variables. Nevertheless, FIML provides a pragmatic approach to handling missing data preferable to other options such as case-wise deletion.

4.6. Conclusion

In conclusion, it remains plausible that there is some low-level limitation in the human brain's speed of information processing which becomes less efficient as we age and which is a contributor to general cognitive decline. An essential step in examining this idea is to have chosen a plausible measure of information processing (one that, such as inspection time, neither resembles a higher-level psychometric test, nor is confounded by possible age-related differences in motor speed) and to have shown that individual differences in its age-related changes are associated with individual differences in general cognitive ageing, as we have done here. With that accomplished, there is still much to do to explain that association.

CRediT authorship contribution statement

Ian J. Deary: Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Simon R. Cox:** Writing – review & editing, Project administration, Funding acquisition, Data curation. **Judith A. Okely:** Writing – original draft, Visualization, Methodology, Formal analysis.

Declaration of competing interest

None declared.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.intell.2024.101844.

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