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Broadband Internet and Cognitive Functioning*

KLAUS ACKERMANN
SoDa Labs and Department of Econometrics and Business Statistics, Monash Business School, Monash University, Melbourne, VIC, Australia

SEFA AWAWORYI CHURCHILL
School of Economics, Finance and Marketing, RMIT University, Melbourne, VIC, Australia

RUSSELL SMYTH
Department of Economics, Monash Business School, Monash University, RMIT University, Melbourne, VIC, Australia

We empirically examine the impact of high-speed internet access on cognitive functioning using data from the Household, Income and Labour Dynamics in Australia survey and crystallised and fluid intelligence measures. Leveraging differences in the National Broadband Network rollout across Australia, we find that high-speed internet access causes a decline in crystallised intelligence and that the effects are mediated by social capital and moderated by age and gender. Although no overall effect on fluid intelligence was observed, a decline was noted in young adults. These findings underline the nuanced influence of high-speed internet access on different aspects of cognitive function.

I Introduction

As of 2020, over 90 per cent of the global population had access to the internet, with most people using the internet daily, particularly in developed countries (International Telecommunication Union, 2020). One survey shows that over three-quarters of Americans went online daily and only approximately one-tenth of the participants, most of whom were elderly, did not use the internet at all (Perrin & Jiang, 2018). In most developed countries, children are exposed to the internet from infancy, with many children spending at least an hour each day using internet-enabled devices (Holloway *et al*., 2013; Kildare & Middlemiss, 2017; Harrison & McTavish, 2018; Huber *et al*., 2018). For instance, the 2015 Programme for International Student Assessment notes that in OECD countries, 95 per cent of 15-year-old children had access to the internet at home. Most children spent more than 2 h each week day online, which represented an increase of 40 min compared to 2012 (OECD, 2017). This is not only the case for adolescents; evidence suggests that most preschoolers and toddlers are exposed to the internet and various digital devices before becoming familiar with books (Hopkins *et al*., 2013).

The increase in prolonged use of the internet, often enabled by high-speed internet access, raises important questions about the impact of the internet and internet speed on cognitive function. As Danovitch (2019) notes in a recent survey of the literature, the empirical evidence on the cognitive effects of the internet to this point has been limited and proved inconclusive. There is some anecdotal evidence to suggest that

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Correspondence: Klaus Ackermann, SoDa Labs and Department of Econometrics and Business Statistics, Monash Business School, Monash University, Melbourne, Vic. 3800, Australia. Email: klaus.ackermann@monash.edu

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internet use may have negative effects on cognitive function. For instance, in a survey conducted by the Pew Research Center, close to 90 per cent of the 2462 participants, who were teachers, agreed that 'today's students have fundamentally different cognitive skills because of the digital technologies they have grown up with' and that the internet was contributing to an 'easily distracted generation with short attention spans'. Yet three-quarters of respondents also indicated that the internet has had a positive impact on students' research and study habits (Purcell *et al*., 2012).

In this paper, we seek to answer the question: How does access to high-speed internet affect cognitive functioning? We measure cognitive function using tests of crystallised and fluid intelligence. Fluid intelligence is the ability to reason and think in abstract as well as solve problems under unique circumstances, independent of acquired knowledge or previous learning experience. Crystallised intelligence refers to the accumulation of different learning experiences, knowledge and skills acquired over time (Wooden, 2013). We use data from the Household, Income and Labour Dynamics in Australia (HILDA) survey, which is a nationally representative panel for the Australian population. We merge HILDA with a new dataset on the adoption of the National Broadband Network (NBN) that we use to measure internet speed at the postcode level. Our identification strategy takes advantage of the timing of the NBN rollout across postcodes, which is uneven. We find that access to high-speed internet causes a decline in crystallised intelligence and that the effect is more pronounced for young adults than middle-aged and older adults. Further, we find evidence of a negative effect of high-speed internet access on fluid intelligence but only for young adults. We examine social capital as a channel of influence and find that social capital is a valid mechanism through which access to high-speed internet transmits to crystallised intelligence.

Most of the related literature on the effects of internet access is from neuroscience, psychology or psychiatry. Our study is most closely related to studies in neuroscience that examine the impact of access to the internet on various constructs related to brain function and cognition (Mills, 2014, 2016; Ioannidis *et al*., 2019). In a recent meta-analysis summarising findings from neuroscience studies that examine the relationship between internet use and cognition, Ioannidis *et al*. (2019) find that problematic internet use is associated with reduced cognition across different psychological domains. We also connect with studies in the psychiatry literature that examine the relationship between internet addiction, personality and various forms of psychiatric diagnosis (Ko *et al*., 2010).[1] Ko *et al*. (2010), for instance, relate internet addiction to various personality traits, whereas other studies in psychology and psychiatry relate internet addiction to disorders such as depression (Kraut *et al*., 1998), anxiety (Shapira *et al*., 2000) and attention deficit disorder (Yoo *et al*., 2004). Related studies in psychiatry have examined the impact of internet addiction on the academic performance of students (see, *e.g*., Ellore *et al*., 2014; Guan & Subrahmanyam, 2009).

Our study is also related to a literature in psychology that has examined the impact of the internet on people's ability to learn and think (Sparrow *et al*., 2011; Rahwan *et al*., 2014). For instance, empirically, Sparrow *et al*. (2011) show that the internet significantly influences the memory of students and their ability to recall specific information and that students were more likely to remember where to access information than to remember the information itself. Rahwan *et al*. (2014) show that the use of networks, such as the internet, tends to limit people's ability to engage in analytical thinking in performing tasks independently.

Many of the existing studies in neuroscience and psychology have had difficulty showing reliable causal estimates, particularly for a representative sample of the population. Kraut *et al*. (1998), who find that greater use of the internet is associated with higher rates of depression and increased loneliness, is one of the few studies to use panel data, but participants were limited to 93 families in Pittsburgh. Some studies have employed an experimental design to draw causal inferences, but these studies typically have nonrepresentative participants and/or small sample sizes. Most of the experimental literature in this area employs a small number of participants who are university students. For example, Sparrow *et al*. (2011), who find that greater use of the internet adversely affects memory recall,

[1] Internet addiction is when a person has a compulsive need to spend an excessive amount time on the Internet, to the point where other areas of their life (*e.g*. relationships, work or health) are allowed to suffer (Ho *et al*., 2014).

report the results of four experiments, in which participants varied between 28 and 60 undergraduate students at Columbia University and Harvard University. The conclusion of Rahwan *et al*. (2014) that the use of networks, such as the internet, reduces the ability to engage in analytical thinking is based on an experiment consisting of 100 undergraduate psychology students at the University of Oregon. One problem is that student subjects are known to represent a 'narrow data base' (Sears, 1986), making it difficult to generalise the conclusions of experiments with student participants to the broader population.[2] A second problem is that much of the neuroscience literature has been criticised more generally for having low average statistical power, meaning that effect sizes are overestimated, making reproducibility difficult (Button *et al*., 2013). Our study has the advantage that we use data on cognitive function from a nationally representative panel, which we are able to link to the uneven rollout of the NBN across postcodes, allowing us to draw reliable causal inferences.[3]

There are a few related studies in the economics literature that use standard economic methods, such as approaches to identification. At a broad level, we contribute to the literature on digital economics that examines whether, and how, digital technology affects economic outcomes (Goldfarb & Tucker, 2019). Within this literature, the studies of Dettling *et al*. (2018) and Sanchis-Guarner *et al*. (2021), who examined the impact of access to broadband or high-speed internet on human capital formation, are closest to ours. Each of these studies uses a similar identification strategy to us in that they exploit variations in supply-side constraints to high-speed internet access based on the rollout of broadband technology.[4] Another closely related study to ours in the economics literature is Malamud *et al*. (2019) who employ a randomised control trial in low-achieving primary schools in Peru in which they compare the effects of three treatment groups on test scores. The three treatments were (i) children who receive laptops with high-speed internet access; (ii) children who receive laptops without internet access; and (iii) children who did not receive laptops. Whereas Dettling *et al*. (2018) and Sanchis-Guarner *et al*. (2021) find that access to high-speed internet increases test scores, Malamud *et al*. (2019) find that the treatment group who had laptops with high-speed internet access did not perform better in terms of test scores than children in the other two treatment groups.

To summarise, we differ from existing studies in two important ways. Most of the neuroscience, psychology and psychiatry literature has focused on the effects of excessive, or problematic, internet use or internet addiction on various outcomes. Rather than focusing on internet use or addiction, we examine the effect of access to high-speed internet. The only studies that consider the effects of access to high-speed internet are a small, but growing, economics literature that exploits variation in broadband internet rollout across space and time, but these studies do not examine the effect of high-speed internet access on cognitive function.

The remainder of the paper is structured as follows. Section II discusses the reasons that conceptually we expect internet speed to affect cognitive function. Section III provides background information on the rollout of the NBN in

[2] For studies that have found students who participate in lab experiments are not representative of the general population in terms of cognition and a variety of other characteristics, see Cappelen *et al*. (2015), Falk *et al*. (2013), Fosgaard (2020) and Snowberg and Yariv (2021).

[3] In Australia, postcodes are used to sort and route mail and represent relatively localised geographical areas. They differ in geographical size between urban and rural areas, reflecting differences in population density. In urban and heavily built-up areas, a postcode is a geographically smaller area, broadly mapping to a suburb of a city, whereas in regional and rural Australia, it typically covers a much larger area, often corresponding to a major regional town and surrounding areas. In 2016 there were 2630 postcodes in Australia. The average area of a postcode is 2911 km^2, with each postcode having an average population of 9075 people.

[4] There are also several recent studies that have proposed similar identification strategies that exploit technological features of the telecommunications infrastructure to model the impact of broadband internet rollout on various outcome. Examples are studies that have modelled the impact of broadband internet rollout on the incidence of sex crimes in Norway (Bhuller *et al*., 2013) and Germany (Diegmann, 2019), election results in Germany (Falck *et al*., 2014), political participation in Italy (Campante *et al*., 2018), labour force participation in the USA (Dettling, 2017) and civic and political engagement in the UK (Geraci *et al*., 2022).

Australia. Section IV describes the data and variables employed in the study. Section V discusses the empirical methodology. Section VI contains the results and discusses the findings and Section VII concludes.

II Why Should Internet Speed Affect Cognition?

Access to high-speed internet could have positive or negative effects on cognitive function. It increases the amount of information that can be easily and quickly accessed on the internet. Among the potential adverse effects, people may not see the need to remember information that can be easily and quickly accessed *via* high-speed internet connections, therefore, impairing various aspects of cognitive function including the ability to memorise (Danovitch, 2019). Being able to more easily and quickly access information by having faster internet connections may make individuals less inquisitive and reduce their ability to think, retain and comprehend information (Tripathi & Ahad, 2017).

Access to faster internet makes people more likely to look up information online than turn to a printed source. Evidence suggests that people remember less when they find information online compared to when they find it in printed materials (Dong & Potenza, 2015). Therefore, although high-speed internet access seems to be an effective channel for information flow, it also influences the thought process. Specifically, with more readily available information online facilitated by having faster internet access, the internet could potentially adversely influence one's ability to be imaginative, contemplative and attentive (Carr, 2008).

Access to high-speed internet may also distort cognitive judgements where people may overestimate their understanding and knowledge of various issues (Ward, 2013; Fisher *et al.*, 2015; Hamilton & Yao, 2018). The illusion of knowledge is likely to lead to diminished curiosity, which has implications for cognitive functioning (Ward, 2013). Similarly, the experience of easily and promptly accessing information or finding answers, enabled by the availability of high-speed internet, can lead to a more laid-back approach to finding answers or reluctance to think appropriately when one encounters more complex problems (Danovitch, 2019). With high-speed internet, people are likely to spend more time on the internet finding answers to questions, rather than thinking thoroughly about them. Therefore, high-speed internet, which makes it easier to access information, can negatively affect information-seeking behaviours.

However, internet speed need not always lead to negative effects on cognitive functioning. The use of high-speed internet potentially facilitates a more efficient allocation, and use, of cognitive resources (Clowes, 2013; Sparrow & Chatman, 2013; Storm & Stone, 2015). Because access to high-speed internet makes it easier to promptly find factual information, remembering such information becomes unnecessary, therefore, allowing one to devote available cognitive resources to interpreting information or better understanding or remembering more complex information that cannot easily be accessed on the internet (Danovitch, 2019).

High-speed internet may also positively influence cognitive functioning by its effect on social interaction and engagement. Individuals with high-speed internet are more likely to be engaged in online social media (Dong *et al.*, 2017). Online social networking sites, such as Facebook and Twitter, help build social capital, enhance social connections and are a source of social support (Ellison *et al.*, 2007; Grieve *et al.*, 2013; Leist, 2013; Vitak & Ellison, 2013). Social capital built online can lead to 'in-person' engagements, and, therefore, high-speed internet could promote social capital in general (Bauernschuster *et al.*, 2014). On the contrary, although high-speed internet access could increase online social capital, it could crowd out 'in-person' social capital if people spend more time on the internet, with overall negative effects on cognitive functioning. Social interaction is an important factor that helps improve or maintain cognitive function, whereas social disengagement impairs cognitive function (Bassuk *et al.*, 1999; Zunzunegui *et al.*, 2003; Barnes *et al.*, 2004; Conroy *et al.*, 2010; Seeman *et al.*, 2010; Myhre *et al.*, 2017). Perceived level of social support and number of social contacts are correlated with various aspects of cognitive function, including episodic memory, working memory, visuospatial ability and perceptual spend, among others (Krueger *et al.*, 2009; Seeman *et al.*, 2010).

High-speed internet access may also contribute to cognitive function by enhancing knowledge transfer (Buchanan, 2011; Voinea *et al.*, 2020). People with high-speed internet access are more likely to use online sources to gather information, which tends to be highly interactive because users have to constantly make decisions about the links to click and the sites to visit. Such interactive activities have been shown to enhance cognitive processes by improving information evaluation, planning and internal cognitive strategies (Johnson, 2008).

The use of high-speed internet is often accompanied by an enhanced requirement to multitasking between different interfaces and platforms, which requires users to shift their attention following different streams of prompts, pop-ups and notifications (Mills, 2014; Firth *et al*., 2019). The need for multitasking can have positive or negative effects on cognitive function. On the one hand, an enhanced ability to multitask can be very useful for performing certain cognitive activities (Firth *et al*., 2019). On the other hand, it is argued that it can interfere with short-term memory and the ability to maintain focus, as well as reduce the concentration needed for certain cognitive tasks (Ophir *et al*., 2009; Loh & Kanai, 2016; Firth *et al*., 2019).

III The NBN Rollout in Australia

The NBN is a nationwide open-access data network project designed to replace the existing plain old telephone service system and satisfy the growing demand in Australia for high-speed internet. The construction of the NBN was first announced by the Australian government in 2009 with the intention to deliver '21st Century Broadband' to all Australians (ACCC, 2009). Although there were a few limited-release sites in 2010 and 2011 restricted to 3000 households at a time, the company formed to oversee the rollout (NBN Co.) announced plans for the first widespread rollout of the NBN in March 2012 (Alizadeh *et al*., 2020). Considered to be the largest nationwide infrastructure project in Australia's history (Egan, 2008), the NBN was expected to significantly improve the speed of internet connectivity, with wired connections providing a minimum of 25 Mbit/s and up to 1000 Mbit/s (Fitzsimmons, 2013). In practice, however, the coverage and the timing of the rollout of the NBN have been very uneven, creating substantial spatial differences in the quality of internet access. Alizadeh (2017) suggests, 'The provision of universal high-speed capacity – as envisaged in the original NBN – has been transformed into a patchwork of final speeds and different quality of service'.

Our identification strategy, which we discuss in more detail in Section V, focuses on the NBN rollout to the end of 2016. Figure 1 shows NBN coverage by postcode at the end of 2016, whereas Figure 2 shows the months since rollout commenced by postcode at the end of 2016. Both figures show that there have been spatial disparities in the rollout of the NBN, in particular, between the major cities and regional areas.[5] Although coverage was reasonably high in the major cities, the rollout of infrastructure was much slower and is more patchy in large areas of regional and rural Australia. This primarily reflects supply-side constraints with laying a fibre-to-the-premises (FttP) network over long distances, given Australia's large landmass (Alizadeh, 2017; Freeman *et al*., 2020). The slow rollout in regional Australia implies that people living in areas outside the main cities have had to predominantly rely on satellite and fixed wireless technologies that offer at best maximum speeds of up to 25 Mbit/s download and 25 bit/s upload (Freeman *et al*., 2020). As a consequence, a review of regional telecommunication performance in 2015 concluded that the NBN has left many rural communities with 'severely limited' internet access (Regional Telecommunications Review, 2015).

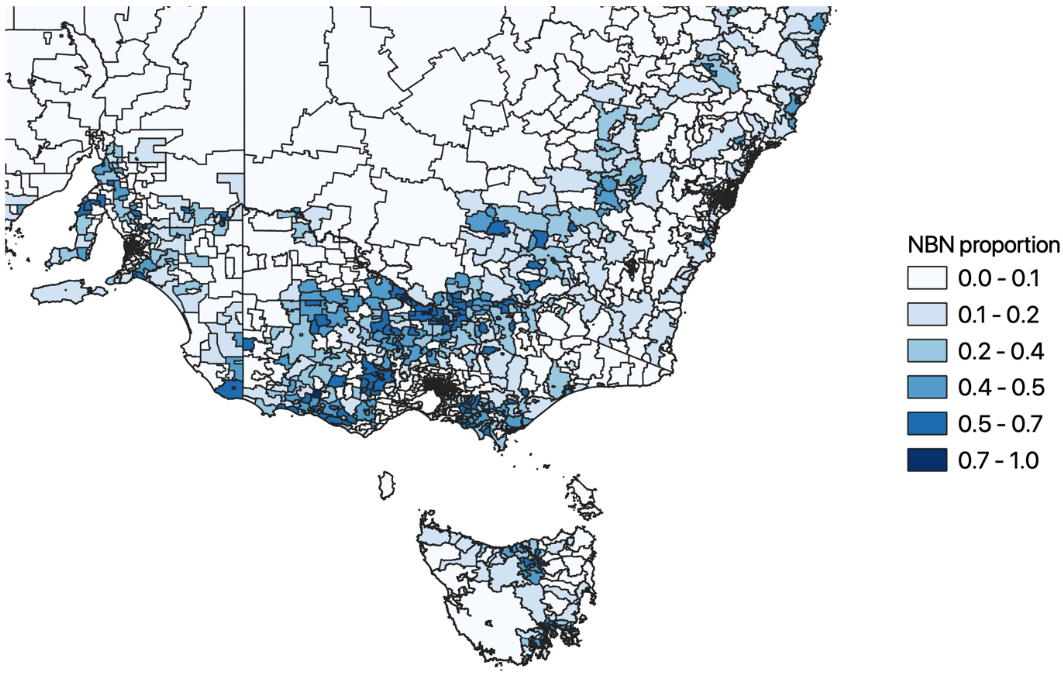
IV Data

Our primary data source is HILDA, which is a nationally representative longitudinal survey, conducted annually since 2001 in Australia. The study design is akin to the British Household Panel Survey and the US Panel Study of Income Dynamics. A wide range of socioeconomic, health and demographic variables are surveyed. We use Release 20 of the unit record survey, which contains 20 waves of annual data from 2001 to 2020. However, we primarily rely on wave 12, administered in 2012, and wave 16, administered in 2016, which are the only two waves in the HILDA survey in which data on cognitive function were collected. Given the cognitive function tests in HILDA are administered to individuals above the age of 15 years (Wooden, 2013), we restrict our sample to participants who are at least 15 years.

We also conduct subsample analyses in which we divide the full sample aged 15–65 years into three subsamples: (i) young adulthood, which comprises respondents aged between 15 and 24 years; (ii) middle adulthood, comprising respondents aged 25–44 years; and (iii) older adulthood for respondents ranging from the ages

[5] In terms of our final household sample, 14 per cent of our respondents have a more than 50 per cent coverage.

FIGURE 1
National Broadband Network (NBN) Proportion in 2016 in Australia by Postcode. [Colour figure can be viewed at wileyonlinelibrary.com]



Note: Zoomed into parts of the states of South Australia, Victoria, New South Wales and Tasmania. This area covers a majority of the population

of 45 to 65 years.[6] After excluding observations with incomplete information,[7] our final sample comprises 10,578 individuals made up of 2564 young adults, 3856 middle-aged adults and 4158 older adults.

(i) Measures of Cognitive Function

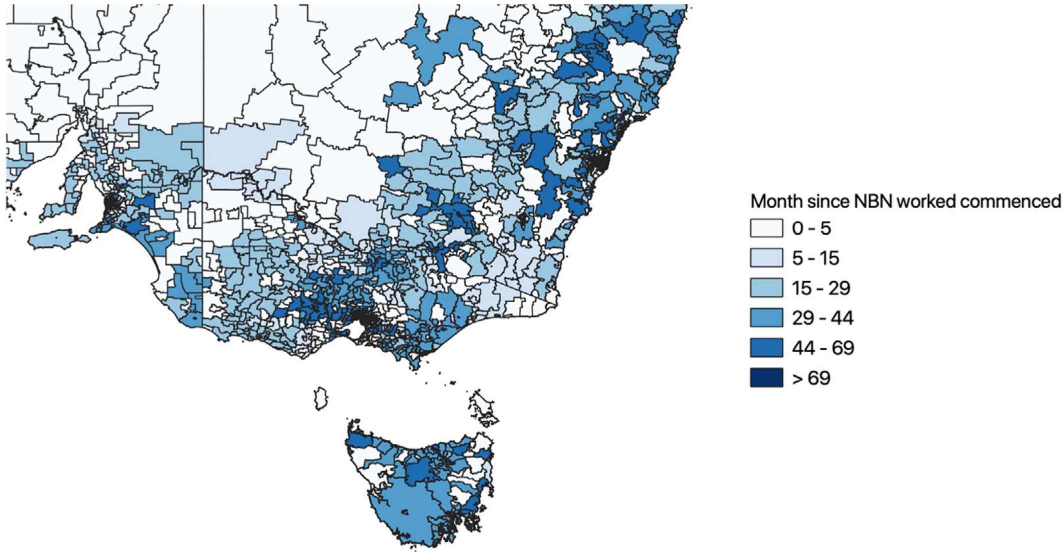
Cognitive functioning refers to different mental abilities, including problem solving, remembering, reasoning, decision making, learning, thinking and attention, that interact to determine an individual's overall intelligence (Fisher *et al.*, 2019; Gong & Zhu, 2019). The HILDA survey contains three tests that are designed to measure different aspects of cognitive function. The three tests, which are described in more detail by Wooden (2013), are (i) a 25-word National Adult Reading Test (NART), (ii) Backwards Digit Span (BDS), and (iii) Symbol Digits Modalities (SDM). Fluid intelligence is measured by the BDS and SDM tests, whereas the NART test is generally considered to be a measure of crystallised intelligence (Ashton *et al.*, 2000; Wooden, 2013; Dohmen *et al.*, 2018; Gong & Zhu, 2019). We conducted a *z*-score normalisation on all three measures, thereby standardising the data.

The NART score, which ranges from 0 to 25, is based on a test that requires participants to read out 25 irregularly spelt words. The score, which represents the sum of the correctly pronounced words, is often used in the literature as an indicator of premorbid intelligence or intellectual ability (see, *e.g.*, Blair & Spreen, 1989; Mathias *et al.*, 2007; Nelson & Willison, 1991; O'Carroll *et al.*, 1992; Rolstad *et al.*, 2008; Willshire *et al.*, 1991).

[6] We follow the definition of the Australian Bureau of Statistics and include all respondents in the working-age range (https://www.abs.gov.au/statistics/standards/age-standard/2014-version-17).

[7] 375 observations are missing.

Figure 2
Month since National Broadband Network (NBN) Work Commenced by Postcode in 2016. [Colour figure can be viewed at wileyonlinelibrary.com]



Note: Zoomed into parts of the states of South Australia, Victoria, New South Wales and Tasmania. This area covers a majority of the population

The BDS test provides a measure of working memory span or short-term memory. It entails interviewers reading out strings of successively longer single-digit numbers that participants are asked to repeat in reverse order. The BDS scores, which range from 0 to 8, represent the highest number of digits that were correctly repeated by the participant. The SDM is a commonly used test used in assessing cognitive processing speed and reflects various dimensions including visual scanning, divided attention and motor speed. The test requires participants to match a set of numbers to various symbols. The SDM score, which ranges from 0 to 100, represents the number of correctly matched items within 90 seconds.

(ii) Internet Speed

We construct a dataset on NBN adoption at the postcode level across Australia. The historical NBN rollout schedule and plan is publicly available on the Telstra wholesale website.[8] Telstra relies on the infrastructure provision by NBN Co., which acts as the statutory infrastructure provider and provides a detailed map of every area covered by the NBN.[9] This information on the rollout dates and areas covered allows us to calculate the proportion of each postcode that had upgraded to the NBN until the end of 2016, as well as when the first upgrade works were completed. Each postcode includes multiple coverage areas and streets, which are upgraded at different times. Thus, for a given postcode, some streets or areas have been upgraded, whereas others have not. Our measure of internet speed is the area of a postcode that has been upgraded as a ratio of the entire postcode. For instance, for a postcode of size 200 m^2, of which 50 m^2 has been upgraded, our measure of NBN rollout, which we refer to as 'proportion of postcode', would be 0.25. We use the confidentialised version of HILDA, which provides information on the postcode in which each respondent resides. This

[8] https://www.telstrawholesale.com.au/nbn/nbn-rollout-schedule.html, last accessed 4 January 2021.

[9] https://data.gov.au/dataset/ds-dga-ed264f72-5fdf-4a54-8381-d35a10c7c85a/details?q=statutory, last accessed 5 January 2021.

allows us to merge individual-level data from the HILDA survey with data on the NBN rollout over time. Given that we focus on cognitive functioning measures drawn from wave 16 of the HILDA survey, we calculate the proportion of postcodes and the time of the first upgrade until the last day of 2016. This approach basically allows us to use an indicator of internet speed that captures the rollout of NBN across different postcodes.

(iii) Covariates

We control for a standard set of demographic and socioeconomic variables collected in HILDA that are likely to influence cognitive functioning. Our covariates include age (in years), household income, employment (binary variables equals 1 if employed), education status (a set of dummy variables representing the highest level of education achieved; we use year 11 as the reference category) and gender (binary variable equals 1 if the respondent is female). We also control for the Big-Five personality traits and locus of control (LoC). The Big-Five personality traits are extroversion, agreeableness, openness, conscientiousness and neuroticism and measure personality at its broadest level of abstraction (John & Srivastava, 1999). LoC is a personality trait that captures the extent to which people believe or feel that they have control over their life (Rotter & Mulry, 1965). On the LoC scale, individuals can be external or internal. Individuals with an external LoC tend to believe that events that occur in their life are outside of their control and can be attributed to factors such as luck, fate and the actions of other people. In contrast, individuals with an internal LoC tend to believe that what happens in their lives results from their own actions and behaviour and they have control over their own lives (Awaworyi Churchill *et al*., 2020; Awaworyi Churchill & Smyth, 2022; Prakash *et al*., 2022). Data on LoC is collected only in waves 3, 4, 7, 11, 15 and 19. We take the average of responses in each wave for which LoC data are available up until wave 11, to rule out any potential cofounding effects following the NBN rollout. Data on the Big-Five personality traits are not available in all waves, and, therefore, we use data from wave 13, which is the nearest wave to wave 16 in which this information was collected. Cobb-Clark and Schurer (2012) show that the Big-Five personality traits are stable in general for working-age adults. In a subsequent study encompassing an extended timeframe, Elkins *et al*. (2017) demonstrate that the personality traits of younger adults may be influenced by alterations in their life circumstances. To eliminate potential confounding effects arising from the sudden availability of high-speed internet, we have limited our analysis to data obtained before this development.

Table A1 provides summary statistics for variables used in this study. The average age of all respondents is approximately 38.75 years. For the subsamples, the average age is 19.70 years for young adults, 33.89 years for middle-aged adults and 54.47 for older adults. The average scores for the NART, BDS and SDM are 13.64, 5.10 and 52.67, respectively. We observe that the NART scores rise with age, whereas BDS and SDM show the opposite trend.

(iv) Social Capital as a Channel

We consider social capital as a potential channel through which internet speed influences cognitive functioning. Our measure of social capital reflects the level of interaction and social contact that a person has with others (Awaworyi Churchill & Farrell, 2020; Appau *et al*., 2022; Trinh *et al*., 2022; Awaworyi Churchill *et al*., 2023). This indicator of social capital is based on a 10-item questionnaire (see Table A2), in which respondents are asked to agree or disagree with 10 statements regarding their level of interaction, social contact and relationships with others. The items on the questionnaire are rated on a seven-point scale, where 1 represents 'strongly disagree' and 7 represents 'strongly agree'. Our measure of social capital is the average of responses from the 10 items on the scale. On this scale, higher (lower) scores represent higher (lower) social capital.

V Empirical Specification and Identification Strategy

To examine the impact of internet speed, proxied *via* the rollout of the NBN connection, on cognitive functioning, we specify the following model:

$$Y_{iL} = \alpha + \beta\,\mathrm{NBN}_L + \gamma\,\mathrm{LoC}_i + \delta\,\mathrm{Big5}_i' + \eta\,X_i' + \epsilon_i \tag{1}$$

where Y_{iL} represents the cognitive functioning score for respondent i living in postcode L; NBN_L is the proportion of postcode L that had the NBN in 2016; LoC_i is the measure of LoC; $\mathrm{Big5}_i'$ is a vector of the Big-Five personality traits; and X_i represents the set of individual explanatory variables including age, age-squared, income, employment, education, dummies for the state or territory, building density and population density.[10] Depending on the specification, we include or exclude a dummy variable for gender.[11]

For our baseline specification, we estimate Equation (1) using OLS and cluster the standard errors at the household level to control for correlations across household members. The relationship between internet speed and cognitive functioning could be endogenous for several reasons. For instance, individuals with higher cognitive skills may self-select into areas with higher internet connectivity. Similarly, endogeneity may arise as a result of omitted variable bias. Thus, in estimation Equation (1), we address endogeneity by adopting a two-stage least squares (2SLS) approach in which we instrument for NBN_L. To correctly identify the causal effects, our instrumental variable (IV) needs to be correlated with NBN_L but have no direct correlation with cognitive functioning, and the only valid mechanism through which the instrument can influence cognitive functioning is *via* NBN_L.

Following the discussion of the characteristics of the NBN rollout in Australia in Section III, to identify the causal effect of internet access on cognitive functioning, we exploit differences in the timing of the NBN rollout across postcodes. Specifically, we instrument for NBN_L using the number of months since the NBN upgrade commenced in a postcode. The proposed IV varies at the postcode level. Postcodes are made up of many different streets and telephone connection points. Thus, the NBN rollout does not fully cover all areas of a postcode when the upgrade begins. In many instances, only a few streets or a specific geographical area within a postcode may initially have access to the NBN, which could continue to be the case for several months. The validity of the timing of the rollout as an IV rests on a set of assumptions that suggest that the rollout of the NBN represents exogenous variation, which is driven by factors not correlated with individual-level cognitive functioning. In the context of our study, as discussed in Section III, the variation in the rollout of the NBN was exogenously driven by technical supply-side constraints associated with laying an FttP network over large distances that are unlikely to covary with key correlates of individual-level cognitive functioning.

VI Results

(i) Baseline Results

Table 1 reports baseline results for the association between NBN rollout and the three measures of cognitive functioning. Column 1 reports results for effects on NART, column 2 reports results for effects on BDS and column 3 reports results for effects on SDM. Across each column, we find that the coefficient on internet speed is statistically insignificant, suggesting that endogeneity is resulting in a downward bias in the estimates.

(ii) Endogeneity Corrected Estimates

Table 2 presents the 2SLS results for the effects of internet speed on cognitive functioning.[12] Column 1 reports findings for the effects on NART. Column 2 reports findings for effects on BDS, whereas Column 3 reports effects on SDM scores. Across all columns, the first-stage *F*-statistics are greater than 104.67, suggesting that at the 5 per cent significance level, our IVs are not weakly correlated with internet speed or the proportion of a postcode that has access to the NBN (Lee *et al*., 2022). The first-stage regression results, which are reported in Table A3, also show that the effects of our instruments on the proportion of a postcode that has access to NBN are consistent with expectations. Specifically, the longer the period since NBN work commenced in a postcode, the higher the proportion of the postcode that has access to the NBN. The results suggest that endogeneity causes a significant downward bias in our baseline results, especially for NART, with the 2SLS estimates being relatively large in magnitude and statistically significant compared to those reported in Table 1.

[10] The data on population density and building density are extracted from the Census Datapack (https://datapacks.censusdata.abs.gov.au/datapacks/). We use the total number of persons and dwellings per postcode, to approximate population and building density by km^2, respectively.

[11] For the young adult cohort, we use a reduced set of covariates comprising age and household income. LoC and Big-5 are collected only for respondents aged above 18 years. Other controls, such as educational attainment, do not present a great deal of variation for this cohort.

[12] The full set of results showing all covariates is reported in Table A4.

Table 1
Internet Speed and Cognitive Functioning (Baseline Results)

Variables	(1) NART	(2) BDS	(3) SDM
NBN proportion	−0.020	0.008	0.043
	(0.046)	(0.046)	(0.042)
	[−0.005]	[0.002]	[0.011]
Observations	9312	9312	9312
R-squared	0.224	0.058	0.251
State fixed effect	Yes	Yes	Yes

Notes: All regressions include as standard set of covariates locus of control, a vector of the Big-Five personality traits, gender, age, age-squared, income, employment, education, dummies for the state or territory, building density and population density. Clustered standard errors are in parentheses. Standardised coefficients are in brackets. BDS, Backwards Digit Span; NART, National Adult Reading Test; NBN, National Broadband Network; SDM, Symbol Digits Modalities.

We find that a 1 per cent increase in the proportion of a postcode that gains access to the NBN causes an average decrease of 0.57 standard deviation in NART scores. Thus, access to high-speed internet causes a decline in crystallised intelligence. The coefficient on NBN proportion is statistically insignificant in columns 2 and 3, in which the dependent variable is BDS and SDM scores, meaning access to high-speed internet has no effect on fluid intelligence.

Table 2
Internet Speed and Cognitive Functioning (2SLS Results)

Variables	(1) NART	(2) BDS	(3) SDM
NBN proportion	−0.569**	−0.087	−0.059
	(0.224)	(0.214)	(0.196)
	[−0.141]	[−0.021]	[−0.014]
Observations	9312	9312	9312
R-squared	0.207	0.057	0.250
State fixed effect	Yes	Yes	Yes
Cragg–Donald Wald F statistic	147.9	147.9	147.9

Notes: $^{**}P < 0.05$. All regressions include as standard set of covariates locus of control, a vector of the Big-Five personality traits, gender, age, age-squared, income, employment, education, dummies for the state or territory, building density and population density. Clustered standard errors are in parentheses. Standardised coefficients are in brackets. 2SLS, two-stage least squares; BDS, Backwards Digit Span; NART, National Adult Reading Test; NBN, National Broadband Network; SDM, Symbol Digits Modalities.

(iii) Heterogeneous Effects by Gender

A large body of literature demonstrates significant differences in internet use patterns for males and females (see, *e.g.*, Li & Kirkup, 2007; McQuillan & Neill, 2009; Morahan-Martin, 1998; Weiser, 2000) and that these differences are likely to influence the impact of access to high-speed internet on cognitive functioning. Therefore, we examine if the impact of access to the NBN on cognitive functioning differs by gender for crystallised intelligence, where we observed a strong statistically significant effect in the full sample. The results are reported in Table 3. Overall, the findings suggest that access to high-speed internet causes a decline in cognitive functioning, although the effect is stronger for males than females.

(iv) Heterogeneous Effects by Age

Motivated by the cognitive aging literature, we explore differences in how NBN rollout affects cognitive functioning by age in Table 4. Panel A

Table 3
Effects of Internet Speed on NART by Gender

Variables	(1) All-female	(2) All-male	(3) Combined
NBN proportion	−0.473**	−0.660**	−0.733***
	(0.240)	(0.309)	(0.243)
	[−0.122]	[−0.158]	[−0.182]
NBN proportion × female			0.299***
			(0.108)
			[0.061]
Observations	4995	4317	9312
R-squared	0.213	0.215	0.206
State fixed effect	Yes	Yes	Yes
Cragg–Donald Wald F statistic	131.5	97.81	73.81

Notes: $^{**}P < 0.05$; $^{***}P < 0.01$. All regressions include as standard set of covariates locus of control, a vector of the Big-Five personality traits, age, age-squared, income, employment, education, dummies for the state or territory, building density and population density. Clustered standard errors are in parentheses. Standardised coefficients are in brackets. NART, National Adult Reading Test; NBN, National Broadband Network.

TABLE 4
Effects of Internet Speed by Age (2SLS)

Variables	(1) Young adults	(2) Middle adults	(3) Older adults
Panel A: National Adult Reading Test (NART)			
NBN proportion	−1.385***	−0.517*	−0.659**
	(0.360)	(0.280)	(0.316)
	[−0.349]	[−0.132]	[−0.161]
Observations	2564	3856	4158
R-squared	−0.007	0.198	0.206
State fixed effect	Yes	Yes	Yes
Cragg–Donald Wald *F* statistic	81.82	105.2	80.17
Panel B: Backwards Digit Span (BDS)			
NBN proportion	−0.542*	−0.001	−0.177
	(0.304)	(0.291)	(0.324)
	[−0.136]	[−0.000]	[−0.044]
Observations	2564	3856	4158
R-squared	0.014	0.067	0.055
State fixed effect	Yes	Yes	Yes
Cragg–Donald Wald *F* statistic	81.82	105.2	80.17
Panel C: Symbol Digits Modalities (SDM)			
NBN proportion	−0.627*	−0.160	−0.032
	(0.362)	(0.253)	(0.249)
	[−0.147]	[−0.040]	[−0.009]
Observations	2564	3856	4158
R-squared	0.031	0.140	0.208
State fixed effect	Yes	Yes	Yes
Cragg–Donald Wald *F* statistic	81.82	105.2	80.17

Notes: $*P < 0.1$; $**P < 0.05$; $***P < 0.01$. All regressions include as standard set of covariates locus of control, a vector of the Big-Five personality traits, gender, age, age-squared, income, employment, education, dummies for the state or territory, building density and population density. Clustered standard errors are in parentheses. Standardised coefficients are in brackets. 2SLS, two-stage least squares; BDS, Backwards Digit Span; NART, National Adult Reading Test; NBN, National Broadband Network; SDM, Symbol Digits Modalities.

reports results for effects on NART, Panel B reports results for effects on BDS and Panel C reports results for effects on SDM. For each panel, we report results for young adults, middle-aged adults, and older adults.

In Columns (1) to (3) of Panel A in Table 4, there is consistent evidence that the effects of NBN access are negative and significant across all age groups. However, the effect of access to high-speed internet is stronger for young adults compared to the other age groups. Specifically, a 1 per cent increase in the proportion of a postcode that gains access to the NBN causes an average decrease of 1.39 standard deviation in NART scores for young adults. This represents a 0.35 standard deviation decrease for a 1 standard deviation increase in faster internet access. This compares with an average decrease of 0.52 (or 0.13 standard deviations) and 0.6 (or 0.16 standard deviations) for middle-aged and older adults, respectively.

The 2SLS estimates from Panel B of Table 4 suggest that the effect of NBN access is significant only in the case of young adults. Here, a 1 per cent increase in the proportion of a postcode that gains access to the NBN causes an average decrease of 0.54 standard deviation in BDS scores for young adults. This represents a 0.14 standard deviation decrease for a 1 standard deviation increase in faster internet access. Compared to the baseline estimates, the coefficient in the young adult specification is larger in magnitude and is now become statistically significant, which reinforces the downward bias associated with endogeneity. Similar patterns are observed in Panel C of Table 4. Here, as well, the effect of NBN access is significant only in the case of young adults. A 1 per cent increase in NBN access causes a decline of 0.63 standard deviation in the SDM scores for young adults with a standardised coefficient of −0.15. Viewed together, the results from Panels B and C suggest that access to high-speed internet causes a decline in fluid intelligence for young adults but not for the older cohorts.

(v) Social Capital as a Mechanism

Section II discusses social capital as a potential mechanism through which internet speed transmits to cognitive functioning. We conduct two sets of analyses focusing on statistically significant relationships. First, in the case of crystallised intelligence, given the effects of NBN access are statistically significant across all specifications, we proceed to examine whether social capital is a channel through which internet speed transmits to crystallised intelligence for the full sample and all the subsamples by age. Second, in the case of BDS and SDM, we conduct our potential channel analysis only for young adults given that the effects of NBN access are significant only for this cohort. Empirical evidence on the relationship between internet speed and social capital is mixed. In some instances, Bauernschuster *et al*. (2014) found that access to fast internet enhanced social capital and that in other instances

TABLE 5
Channel Analysis by Age – Crystalised Intelligence (NART)

Variables	(1) Social capital	(2) All	(3) Young adults	(4) Middle adults	(5) Older adults
NBN proportion	−1.051***	−0.412*	−1.016***	−0.435	−0.409
	(0.245)	(0.222)	(0.207)	(0.303)	(0.286)
	[−0.251]	[−0.103]	[−0.215]	[−0.111]	[−0.101]
Social capital		0.047***	0.043**	0.043***	0.058***
		(0.010)	(0.020)	(0.015)	(0.016)
		[0.049]	[0.049]	[0.049]	[0.056]
Observations	8282	8282	2146	3353	3834
R-squared	−0.001	0.222	0.020	0.210	0.227
State fixed effect	Yes	Yes	Yes	Yes	Yes
Cragg–Donald Wald *F* statistic	136.4	136.2	72.52	90.56	86.35

Notes: *$P < 0.1$; **$P < 0.05$; ***$P < 0.01$. All regressions include as standard set of covariates, locus of control, a vector of the Big-Five personality traits, gender, age, age-squared, income, employment, education, dummies for the state or territory, building density and population density. Clustered standard errors in parentheses. Standardised coefficients in brackets. NART, National Adult Reading Test; NBN, National Broadband Network.

the effect was insignificant. Geraci *et al*. (2022) find that access to fast internet caused a significant decline in civic and political engagement in the UK, employing a strategy that exploited a technological feature of the telecommunications infrastructure that generated variation in internet quality between households. In light of the results of Geraci *et al*. (2022), we expect that by substituting time spent online for face-to-face interaction, NBN access is likely to diminish social capital and with it, cognitive function, which tends to be associated with social capital.

For social capital to qualify as a mechanism in the NBN access-cognitive functioning relationship, in addition to being correlated with NBN access, it should be correlated with our measure of cognitive functioning. Further, the inclusion of social capital as an additional control variable in the regression linking NBN access to cognitive functioning should decrease the magnitude of the coefficient on NBN access or render it statistically insignificant.

In Column 1 of Table 5, we estimate the effect of the NBN rollout on social capital. We find a strong negative effect. Specifically, a 1 per cent increase in the proportion of a postcode that gains access to NBN is associated with an average decrease of 1.05 in social capital. This effect size suggests a decline of 0.25 standard deviation for a standard deviation increase in NBN access, which represents a large effect. In Columns 2 to 5 of Table 5, we include social capital as an additional covariate in the crystallised intelligence specifications. In each column, an increase in social capital is associated with an increase in crystallised intelligence. Further, we note that with the inclusion of social capital as an additional covariate in the model, the coefficient on NBN access either reduces in magnitude (Columns 2 and 3) or becomes statistically insignificant (Columns 4 and 5). These results confirm social capital as a mechanism through which NBN access transits to crystallised intelligence.

In Table 6, we focus on fluid intelligence among young adults. Consistent with the findings presented in Table 5, we find that NBN access is associated with a decline in the level of social capital of young adults. In Columns 2 and 3, we include social capital as an additional covariate in the specifications for fluid intelligence for the young adult subsample. The coefficient on social capital is statistically insignificant. Therefore, social capital is not a channel through which access to high-speed internet transmits fluid intelligence among young adults.

(vi) Robustness Checks

In Table A5, we conduct a placebo test to examine the validity of our 2SLS estimates reported in Table 2. We follow Bhuller *et al*. (2013) and repeat our 2SLS estimation in 2012, with the 2016 NBN proportion and instrument. As these scores predated the NBN rollout, significant estimates would suggest that

TABLE 6
Channel Analysis – Fluid Intelligence for Young Adults (BDS and SDM)

Variables	(1) Social capital	(2) BDS	(3) SDM
NBN proportion	−0.900**	−0.608*	−0.477
	(0.422)	(0.343)	(0.367)
	[−0.205]	[−0.153]	[−0.115]
Social capital		0.022	0.027
		(0.020)	(0.022)
		[0.024]	[0.028]
Observations	2146	2146	2146
R-squared	−0.026	0.016	0.036
State fixed effect	Yes	Yes	Yes
Cragg–Donald Wald *F* statistic	71.07	72.52	72.52

Notes: $*P < 0.1$; $**P < 0.05$. All regressions include as standard set of covariates, locus of control, a vector of the Big-Five personality traits, gender, age, age-squared, income, employment, education, dummies for the state or territory, building density and population density. Clustered standard errors are in parentheses. Standardised coefficients are in brackets. BDS, Backwards Digit Span; NBN, National Broadband Network; SDM, Symbol Digits Modalities.

the IV is correlated with underlying postcode-specific trends in cognitive function. However, we find no evidence that our instrument is correlated with postcode characteristics that might otherwise drive our results.

We have argued that variation in the rollout of the NBN was exogenously driven by technical supply-side constraints. One might be worried that these supply-side constraints could be related to population density and urban/rural characteristics of localities and, therefore, likely to be correlated with educational attainment and cognitive skills. In a robustness check, we re-estimate our main specification to include a binary variable to account for respondents living in a major city. In Table A6, we provide further evidence that when we condition on urban to rural characteristics of a postcode, our results remain robust. The inclusion of this variable ensures that our results are robust to any correlation that may exist between our instrument and the built environment.

As a further check on the 2SLS estimates, we take advantage of knowing the cognitive test scores in the 2012 wave and employ a difference-in-difference (DID) design, which is similar in approach to that employed in Diegmann (2019). We define a postcode as treated if the NBN coverage is greater than 1 per cent in 2016.[13] Given that the NBN rollout commenced only in 2012, we use the 2012 cognitive function test results in HILDA as the pretreatment outcome.[14]

Specifically, we estimate the following model:

$$Y_{itL} = \alpha + \beta D_{tL} + \gamma \, \mathrm{LoC}_i + \delta \, \mathrm{Big5}'_i + \eta X'_{it} + \lambda_t + \xi_L + \epsilon_{it} \quad (2)$$

where Y_{itL} represents the cognitive functioning score for respondent i living in postcode L at time t; D_{tL} is the treatment of interest – getting access to high-speed internet in 2016; LoC_i is LoC; $Big5'_i$ is a vector of the Big-Five personality traits; X_{it} represents the set of individual explanatory variables including age, age-squared, income, employment and education; λ_t is a time dummy, which is 1 in 2016; and ξ_L is a dummy for the postcode if it ever gets access to fast internet. With this approach, we estimate the extensive margin.

In Table A7, we report results from the DID estimation approach in Equation (2). The results are robust, and the DID results reinforce the finding that access to high-speed internet causes a decline in crystallised intelligence but not fluid intelligence.

As a further check, we re-estimate our main specification with 2SLS but cluster the standard errors on the postcode level in Table A8. Our results remain robust. Similarly, for the DID estimation, we cluster at the postcode level, although for the panel data structure, we are also able to include a household fixed effect in Table A9, and the results remain consistent.

As the NART score is a language type of test, it might be influenced by the main language spoken at home. In Table A10, we control for the main language spoken at home and the results remain robust.

[13] We also used 5, 10 and 15 per cent as cut-offs, and the results remained robust.

[14] As mentioned in Section III, the NBN was piloted in a few select sites in 2010 and 2012, but plans for more widespread rollout were only announced in March 2012, and the initial rollout in the remainder of 2012 was very slow and limited. By the end of 2012, only 0.5% of postcodes in Australia had any NBN coverage. We re-estimated the model excluding postcodes with any NBN coverage in 2012 and the main conclusions remain unaltered.

Finally, between Tables 1 and 2, the OLS results are biased downwards compared to the IV results. To explore the reasons for the downward bias in the OLS estimates, we employ a method proposed by Ishimaru (2023) to decompose the gap. Ishimaru (2023) shows that, in general, the IV–OLS coefficient gap consists of three estimable components: the difference in weights on the covariates, the difference in weights on the treatment levels and the difference in identified marginal effects that arise from endogeneity bias.

The decomposition results employing the approach in Ishimaru (2023) presented in Table A11 reveal a significant downward bias in the OLS estimates when compared to the IV estimates. This gap can partially be explained by differences in covariate weights and treatment-level weights; however, the majority of the downward bias can be attributed to the marginal effect. This finding suggests that there may be considerable endogeneity or omitted variable bias in the OLS estimates. A closer examination of the geographic variables in Table A12 further highlights the discrepancies in weights between the OLS and IV models.

The observed downward bias in the OLS estimates can be ascribed to the instrument's ability to capture unobserved factors and isolate exogenous variation in NBN coverage, particularly the temporal and spatial variation across postcodes. By utilising the data since the rollout started as an instrument and considering the postcode-level variation, our analysis provides a more accurate estimation of the causal effect of NBN coverage on NART outcomes.

(vii) Discussion of Results

We find that NBN access causes a decline in crystallised intelligence and that the observed negative effect on cognition is strongest for young adults compared to middle-aged and older adults. We also find that NBN access has a negative effect on fluid intelligence but only for young adults. The finding that, overall, NBN access has a stronger negative effect on cognitive function for young adults is consistent with young adults spending relatively more time online, which makes them more susceptible to the effects of high-speed internet (Burns *et al.*, 2010; Morrison & Gore, 2010). The finding that NBN access has a negative effect on fluid intelligence only for young adults is consistent with the literature, which suggests that fluid intelligence is more easily influenced at younger ages (Fry & Hale, 1996, 2000). The evidence from the neuroscience literature is that improvements in fluid intelligence are nonlinear in young adulthood and then flatten out in one's late teens and early 20s (Fry & Hale, 2000). The reasons for this are not well understood but are likely linked to neurological developments in the brain's ability to reason and think in the abstract (Fry & Hale, 2000).

The finding that the effects of internet speed on cognitive function are stronger for crystallised intelligence than fluid intelligence is consistent with the internet, primarily affecting cognitive function *via* its role as a source of knowledge. If the internet creates the illusion of knowledge (Ward, 2013; Fisher *et al.*, 2015; Hamilton & Yao, 2018) or makes people overconfident about the knowledge or skills that they have accumulated over time, this will adversely affect crystallised intelligence. High-speed internet access could also influence fluid intelligence by the effect of multitasking on abstract reasoning. That high-speed internet access affects fluid intelligence for younger adults but not middle-aged and older adults suggests that younger adults might be more likely to use the internet in an interactive way and to become distracted from multitasking with adverse implications for abstract reasoning. This conjecture is consistent with evidence from the computer science literature that younger cohorts are more likely to engage in electronic and nonelectronic multitasking and that engaging in a wider range of tasks is associated with feeling more distracted (Zwarun & Hall, 2014).

We find that gender moderates the effect of high-speed internet access on crystallised intelligence and that the effects are stronger for males. One factor contributing to this result could be that males tend to spend more time online than females (Morahan-Martin, 1998). Therefore, perceived acquired knowledge and learned experiences *via* the internet may be higher for men than women. Another consideration is that men are more likely to be overconfident than women in their ability across a range of domains (see Barber & Odean, 2001; Bengtsson *et al.*, 2005). This is especially so in perceptions of knowledge accumulation. For example, Nekby *et al.* (2015) find that males tend to be overconfident about what they know in exam settings. These factors together suggest that the illusion of knowledge created by the internet and overconfidence in what one knows as a result of engaging with high-speed internet may be higher among men than women with adverse effects on crystallised intelligence.

We examine social capital as a channel of influence and find that social capital is a valid mechanism through which access to high-speed internet transmits to crystallised intelligence but not fluid intelligence. Social capital represents an important source of acquired knowledge (Wei *et al*., 2011) and learned experiences (Lee & Bell, 2013). The acquisition of knowledge and learned experiences through social engagement over time contributes to crystallised intelligence, whereas fluid intelligence depends on the ability to solve problems in the abstract, independent of accumulated knowledge over time. Therefore, experiences and knowledge acquired through accumulating social capital are less likely to influence fluid intelligence.

VII Conclusion

Considered the most rapidly adopted and widespread technology in history, the internet has completely altered many ways of doing things. In response to the persistent increase in internet use across different age groups, there has been an increase in research that explores the association between internet use, technology access and various cognitive and noncognitive outcomes. Understanding the factors that influence cognitive functioning is important for optimising performance and productivity. A growing body of literature has examined the relationship between internet use and various dimensions of cognition or brain function in psychology and neuroscience. These studies, though, have tended to focus on internet addiction or excessive internet use and relied on small, nonrepresentative samples, both of which limit the extent to which conclusions from this literature can be generalised to the broader population.

Our contribution has been to examine the impact of access to high-speed internet on three indicators of cognitive functioning, capturing crystallised and fluid intelligence using data from HILDA, which is a nationally representative survey of the Australian population. To measure high-speed internet, we construct a new dataset on NBN adoption at the postcode level across Australia and use differences in the timing of the NBN rollout to address the endogenous relationship between NBN access and cognitive functioning. We find that high-speed internet access causes a decline in crystallised intelligence for the full sample and that the effects are mediated by social capital and moderated by age and gender. We also find that high-speed internet access causes a decline in fluid intelligence, but this result only holds for young adults.

One important policy implication that stems from our result is addressing social capital as a channel. Our findings suggest that by diminishing social capital, access to high-speed internet negatively influences cognitive function in the form of crystallised intelligence, especially among young adults. These findings point to the need for measures that foster social capital amid the growing use of the internet. Admittedly, such measures might include the need for moderation, especially among young adults. Measures to reduce reliance on the internet are likely to build stronger social capital and promote better cognition.

Conflict of interest

The author's declare no conflict of interest.

Data Availability Statement

The underlying household survey cannot be shared publicly. It is available to any researcher via a request here: https://melbourneinstitute.unimelb.edu.au/hilda.

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Appendix I

TABLE A1
Summary Statistics

Variables	Mean	Standard deviation	Min	Max
Premorbid intelligence (NART)	13.64	5.27	0.00	25.00
Working memory (BDS)	5.10	1.44	0.00	8.00
Executive function (SDM)	52.65	11.08	5.00	110.00
Female	0.52	0.50	0.00	1.00
Age	38.75	14.46	15.00	65.00
Disposable household income in log	11.37	0.66	5.27	13.80
Employed	0.74	0.44	0.00	1.00
Postgrad	0.06	0.24	0.00	1.00
Grad diploma	0.06	0.24	0.00	1.00
Bachelor	0.16	0.37	0.00	1.00
Advanced diploma	0.10	0.30	0.00	1.00
Certificate 3 or 4	0.24	0.43	0.00	1.00
Language	0.13	0.34	0.00	1.00
Locus of control	5.45	0.91	1.36	7.00
Extroversion	4.45	1.11	1.00	7.00
Agreeableness	5.44	0.89	1.00	7.00
Conscientiousness	5.08	1.02	1.00	7.00
Emotional stability	5.08	1.07	1.00	7.00
Openness to experience	4.32	1.04	1.00	7.00
Population density	1384.06	1685.83	0.02	15,130.27
Building density	566.52	761.50	0.00	8146.19
Month since NBN work commenced	26.12	23.38	0.00	207.00
NBN proportion	0.17	0.24	0.00	0.99

Note: BDS, Backwards Digit Span; NART, National Adult Reading Test; NBN, National Broadband Network; SDM, Symbol Digits Modalities.

TABLE A2
Items on Social Capital Scale

	The following statements have been used by many people to describe how much support they get from other people. How much do you agree or disagree with each?	Response scale
1	People do not come to visit me as often as I would like (reverse coded)	Strongly disagree (1) ... strongly agree (7)
2	I often need help from other people but cannot get it (reverse coded)	Strongly disagree (1) ... strongly agree (7)
3	I seem to have a lot of friends	Strongly disagree (1) ... strongly agree (7)
4	I do not have anyone that I can confide in (reverse coded)	Strongly disagree (1) ... strongly agree (7)
5	I have no one to lean on in times of trouble (reverse coded)	Strongly disagree (1) ... strongly agree (7)
6	There is someone who can always cheer me up when I'm down	Strongly disagree (1) ... strongly agree (7)
7	I often feel very lonely (reverse coded)	Strongly disagree (1) ... strongly agree (7)
8	I enjoy the time I spend with the people who are important to me	Strongly disagree (1) ... strongly agree (7)
9	When something's on my mind, just talking with the people I know can make me feel better	Strongly disagree (1) ... strongly agree (7)
10	When I need someone to help me out, I can usually find someone	Strongly disagree (1) ... strongly agree (7)

TABLE A3
First Stage Regression

Variables	(1) First stage
Month since NBN work commenced	0.0023***
	(0.0002)
Female	0.0046
	(0.0038)
Age	−0.0026*
	(0.0014)
Age-squared	0.0000**
	(0.0000)
Disposable household income in log	−0.0106*
	(0.0054)
Employed	−0.0003
	(0.0065)
Postgrad	−0.0206*
	(0.0112)
Grad diploma	−0.0014
	(0.0107)
Bachelor	0.0115
	(0.0079)
Advanced diploma	−0.0080
	(0.0082)
Certificate 3 or 4	0.0047
	(0.0066)
Locus of control	0.0000
	(0.0033)
Extroversion	0.0009
	(0.0023)
Agreeableness	−0.0007
	(0.0030)
Conscientiousness	−0.0004
	(0.0027)
Emotional stability	0.0004
	(0.0026)
Openness to experience	−0.0017
	(0.0027)
Population density	−0.0001***
	(0.0000)
Building density	0.0002***
	(0.0000)
Observations	9312
State fixed effect	Yes
F-statistics	147.9

Notes: *$P < 0.1$; **$P < 0.05$; ***$P < 0.01$. Clustered standard errors are in parentheses.

Table A4
Full 2SLS Results

Variables	(1) NART	(2) BDS	(3) SDM
NBN proportion	−0.569**	−0.087	−0.059
	(0.224)	(0.214)	(0.196)
	[−0.141]	[−0.021]	[−0.014]
Female	0.052***	0.008	0.283***
	(0.018)	(0.021)	(0.019)
	[0.027]	[0.004]	[0.143]
Age	0.001	0.007	−0.002
	(0.005)	(0.005)	(0.005)
	[0.018]	[0.093]	[−0.030]
Age-squared	0.000	−0.000**	−0.000***
	(0.000)	(0.000)	(0.000)
	[0.112]	[−0.144]	[−0.344]
Disposable household income in log	0.116***	0.072***	0.111***
	(0.018)	(0.018)	(0.017)
	[0.080]	[0.048]	[0.075]
Employed	0.074***	0.072***	0.219***
	(0.025)	(0.026)	(0.024)
	[0.032]	[0.030]	[0.093]
Postgrad	0.586***	0.390***	0.366***
	(0.044)	(0.046)	(0.039)
	[0.152]	[0.098]	[0.093]
Grad diploma	0.588***	0.232***	0.326***
	(0.041)	(0.047)	(0.040)
	[0.150]	[0.058]	[0.082]
Bachelor	0.496***	0.289***	0.320***
	(0.028)	(0.033)	(0.028)
	[0.194]	[0.110]	[0.123]
Advanced diploma	0.193***	0.058	0.145***
	(0.032)	(0.036)	(0.032)
	[0.061]	[0.018]	[0.045]
Certificate 3 or 4	−0.046*	−0.081***	−0.064***
	(0.025)	(0.026)	(0.025)
	[−0.020]	[−0.035]	[−0.028]
Locus of control	0.095***	0.066***	0.080***
	(0.013)	(0.013)	(0.012)
	[0.087]	[0.059]	[0.072]
Extroversion	−0.061***	−0.008	−0.041***
	(0.008)	(0.010)	(0.008)
	[−0.069]	[−0.009]	[−0.045]
Agreeableness	−0.048***	−0.036***	−0.041***
	(0.012)	(0.013)	(0.012)
	[−0.044]	[−0.032]	[−0.037]
Conscientiousness	−0.059***	−0.015	0.056***
	(0.010)	(0.011)	(0.010)
	[−0.062]	[−0.015]	[0.058]
Emotional stability	0.083***	0.038***	0.030***
	(0.010)	(0.011)	(0.010)
	[0.091]	[0.040]	[0.032]
Openness to experience	0.243***	0.068***	0.068***
	(0.010)	(0.011)	(0.010)

Table A4
(continued)

Variables	(1) NART	(2) BDS	(3) SDM
	[0.259]	[0.070]	[0.071]
Population density	−0.000***	−0.000	−0.000
	(0.000)	(0.000)	(0.000)
	[−0.296]	[−0.065]	[−0.046]
Building density	0.000***	0.000	0.000
	(0.000)	(0.000)	(0.000)
	[0.340]	[0.090]	[0.078]
Observations	9312	9312	9312
R-squared	0.207	0.057	0.250
State fixed effect	Yes	Yes	Yes
Cragg–Donald Wald *F* statistic	147.9	147.9	147.9

Notes: *$P < 0.1$; **$P < 0.05$; ***$P < 0.01$. Clustered standard errors are in parentheses.

Table A5
Robustness Check and 2SLS Estimation with Lagged Outcome Variable

Variables	(1) NART 2012	(2) BDS 2012	(3) SDM 2012
Panel A: OLS estimation			
NBN proportion	−0.018	−0.034	−0.053
	(0.045)	(0.048)	(0.043)
	[−0.005]	[−0.008]	[−0.013]
Observations	8515	8515	8515
R-squared	0.249	0.058	0.215
State fixed effect	Yes	Yes	Yes
Panel A: 2SLS estimation			
NBN proportion	−0.243	−0.132	−0.249
	(0.243)	(0.228)	(0.200)
	[−0.061]	[−0.032]	[−0.063]
Observations	8515	8515	8515
R-squared	0.247	0.057	0.212
State fixed effect	Yes	Yes	Yes

Notes: All regressions include as standard set of covariates locus of control, a vector of the Big-Five personality traits, gender, age, age-squared, income, employment, education, dummies for the state or territory, building density and population density. Clustered standard errors are in parentheses. Standardised coefficients are in brackets. 2SLS, two-stage least squares; BDS, Backwards Digit Span; NART, National Adult Reading Test; NBN, National Broadband Network; SDM, Symbol Digits Modalities.

Table A6
Robustness Check and 2SLS Estimation Controlling for Local Characteristics

	(1)	(2)	(3)
Variables	NART	BDS	SDM
NBN proportion	−0.523**	−0.093	−0.040
	(0.255)	(0.241)	(0.223)
	[−0.130]	[−0.022]	[−0.010]
Living in a major city	0.041	−0.005	0.017
	(0.041)	(0.039)	(0.037)
	[0.020]	[−0.002]	[0.008]
Observations	9312	9312	9312
R-squared	0.210	0.057	0.251
State fixed effect	Yes	Yes	Yes
Cragg–Donald Wald *F* statistic	138.3	138.3	138.3

Notes: $^{**}P < 0.05$. All regressions include as standard set of covariates locus of control, a vector of the Big-Five personality traits, gender, age, age-squared, income, employment, education, dummies for the state or territory, building density and population density. Clustered standard errors are in parentheses. Standardised coefficients are in brackets. 2SLS, two-stage least squares; BDS, Backwards Digit Span; NART, National Adult Reading Test; NBN, National Broadband Network; SDM, Symbol Digits Modalities.

Table A7
Internet Speed and Cognitive Functioning (Difference in Difference Estimation)

	(1)	(2)	(3)
Variables	NART	BDS	SDM
DID Estimation	−0.058**	0.046	0.147
	(0.029)	(0.042)	(0.294)
	[−0.026]	[0.014]	[0.006]
Observations	19,768	19,768	19,768
R-squared	0.242	0.059	0.232
State fixed effect	Yes	Yes	Yes

Notes: $^{**}P < 0.05$. All regressions include as standard set of covariates locus of control, a vector of the Big-Five personality traits, gender, age, age-squared, income, employment, education, dummies for the state or territory, building density and population density. Clustered standard errors are in parentheses on the household level. Standardised coefficients are in brackets. DID, difference in difference.

TABLE A8
Internet Speed and Cognitive Functioning (2SLS) and Clustering on Postcode Level

Variables	(1) NART	(2) BDS	(3) SDM
NBN proportion	−0.569**	−0.087	−0.059
	(0.280)	(0.225)	(0.207)
	[−0.141]	[−0.021]	[−0.014]
Observations	9312	9312	9312
R-squared	0.207	0.057	0.250
State fixed effect	Yes	Yes	Yes
Cragg–Donald Wald *F* statistic	21.67	21.67	21.67

Notes: $^{**}P < 0.05$. All regressions include as standard set of covariates locus of control, a vector of the Big-Five personality traits, gender, age, age-squared, income, employment, education, dummies for the state or territory, building density and population density. Clustered standard errors on the postcode level are in parentheses. Standardised coefficients are in brackets. 2SLS, two-stage least squares; BDS, Backwards Digit Span; NART, National Adult Reading Test; NBN, National Broadband Network; SDM, Symbol Digits Modalities.

TABLE A9
Internet Speed and Cognitive Functioning (DID Estimation) and Clustering on Postcode Level

Variables	(1) NART	(2) BDS	(3) SDM
Panel A			
DID estimation	−0.058**	0.046	0.153
	(0.024)	(0.036)	(0.232)
	[−0.026]	[0.014]	[0.006]
Observations	19,768	19,768	19,768
R-squared	0.244	0.059	0.252
State fixed effect	Yes	Yes	Yes
Household fixed effect	No	No	No
Panel B			
DID estimation	−0.105**	0.034	0.552
	(0.050)	(0.068)	(0.517)
	[−0.048]	[0.011]	[0.023]
Observations	19,768	19,768	19,768
R-squared	0.653	0.511	0.615
State fixed effect	Yes	Yes	Yes
Household fixed effect	Yes	Yes	Yes

Notes: $^{**}P < 0.05$. All regressions include as standard set of covariates, locus of control, a vector of the Big-Five personality traits, gender, age, age-squared, income, employment, education, dummies for the state or territory, building density and population density. Clustered standard errors are in parentheses on the postcode level. Standardised coefficients are in brackets. BDS, Backwards Digit Span; DID, difference in difference; NART, National Adult Reading Test; SDM, Symbol Digits Modalities.

Table A10
Robustness Check and 2SLS Estimation Controlling for Language

Variables	(1) NART	(2) BDS	(3) SDM
NBN proportion	−0.401**	−0.026	−0.031
	(0.204)	(0.208)	(0.193)
	[−0.100]	[−0.006]	[−0.008]
Language	−0.612***	−0.224***	−0.100***
	(0.035)	(0.032)	(0.031)
	[−0.214]	[−0.076]	[−0.034]
Observations	9312	9312	9312
R-squared	0.256	0.063	0.252
State fixed effect	Yes	Yes	Yes
Cragg–Donald Wald F statistic	150.8	150.8	150.8

Notes: $^{**}P < 0.05$; $^{***}P < 0.01$. All regressions include as standard set of covariates locus of control, a vector of the Big-Five personality traits, gender, age, age-squared, income, employment, education, dummies for the state or territory, building density and population density. Language is a dummy variable, that is, one if the main language spoken at home is not English. Clustered standard errors are in parentheses. Standardised coefficients are in brackets. 2SLS, two-stage least squares; BDS, Backwards Digit Span; NART, National Adult Reading Test; NBN, National Broadband Network; SDM, Symbol Digits Modalities.

Table A11
Decomposition of the IV–OLS Gap in Internet and NART Estimates

Coefficients			Decomposition		
OLS	IV	IV–OLS Gap	Covariate weight difference	Treatment-level weight difference	Marginal effect difference
−0.020	−0.569	−0.548	−0.090	0.033	−0.491
(0.039)	(0.180)	(0.175)	(0.033)	(0.019)	(0.170)

Notes: Standard errors are in parentheses. Decomposition method proposed by Ishimaru (2023). IV, instrumental variable; NART, National Adult Reading Test.

Table A12
The IV and OLS Weights on the Covariate Groups

Variables	Group	Group share	OLS weight	IV weight
Major city	Yes	0.654	0.621 (0.010)	0.583 (0.019)
	No	0.346	0.379 (0.010)	0.417 (0.019)
Population density quantiles	Q1	0.250	0.203 (0.006)	0.198 (0.015)
	Q2	0.251	0.196 (0.007)	0.243 (0.017)
	Q3	0.254	0.395 (0.011)	0.309 (0.019)
	Q4	0.245	0.206 (0.010)	0.249 (0.018)
Building density quantiles	Q1	0.253	0.205 (0.006)	0.198 (0.015)
	Q2	0.247	0.191 (0.007)	0.256 (0.017)
	Q3	0.256	0.382 (0.011)	0.308 (0.020)
	Q4	0.244	0.222 (0.010)	0.239 (0.017)
State or territory	New South Wales	0.286	0.328 (0.011)	0.073 (0.023)
	Victoria	0.255	0.176 (0.007)	0.261 (0.017)
	Queensland	0.212	0.182 (0.008)	0.33 (0.017)
	South Australia	0.092	0.11 (0.007)	0.112 (0.011)
	Western Australia	0.088	0.107 (0.006)	0.096 (0.011)
	Tasmania	0.035	0.053 (0.004)	0.054 (0.008)
	Northern Territory	0.008	0.007 (0.001)	0.014 (0.003)
	Australian Capital Territory	0.023	0.039 (0.006)	0.059 (0.008)

Notes: Standard errors are in parentheses. Decomposition method proposed by Ishimaru (2023). IV, instrumental variable.