Journal of Experimental Child Psychology 219 (2022) 105412

Contents lists available at ScienceDirect

Journal of Experimental Child Psychology

journal homepage: www.elsevier.com/locate/jecp

# Longitudinal development of cognitive mapping from childhood to adolescence

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ARTICLE INFO

*Article history:*
Received 26 October 2021
Revised 16 February 2022
Available online 7 March 2022

*Keywords:*
Virtual environment
Spatial cognition
Development
Navigation
Cognitive map
Perspective taking

ABSTRACT

Cross-sectional studies have suggested that the ability to form cognitive maps increases throughout childhood and reaches adult levels during early adolescence. However, adults show large individual differences in their ability to relate local routes to form a global map. Children also vary, but when does variation stabilize? We asked participants from a previously published cross-sectional study [*Journal of Experimental Child Psychology* (2018), Vol. 170, pp. 86–106] to return for a second session of testing 3 years later to examine whether longitudinal stability is more evident at older ages. The subsample of 50 of the original 105 participants available for retesting did not differ from the original sample on male–female ratio or Session 1 task performance. We reassessed performance on the Virtual Silcton navigation paradigm, the Spatial Orientation Test (SOT), and the Mental Rotation Test (MRT) and added parents' scores on the SOT and MRT at Timepoint 2. Our initial analyses of normative development aligned with prior cross-sectional findings; overall navigation performance reached adult levels of proficiency around 12 years of age. In addition, variation in route integration abilities, as measured by between-route pointing, stabilized around 12 years of age; that is, longitudinal stability was higher in the older cohort than in the younger cohort. The same pattern appeared for the MRT.



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https://doi.org/10.1016/j.jecp.2022.105412

## Introduction

Navigating large-scale environments is important for many everyday activities. Successful navigation requires manipulation and integration of multisensory information across space and time (Wolbers & Hegarty, 2010) using several possible strategies. One strategy for successful navigation is to associate environmental and self-motion cues with specific action sequences in memory, thereby allowing wayfinding along a fixed route. However, this approach does not allow finding a more direct route to a final goal that is not within sight (i.e., taking a shortcut). Furthermore, using this action sequence strategy may leave travelers lost if they become disoriented or if there is an unexpected change to the environment. More flexible and powerful strategies for navigation use an allocentric reference frame that allows for detours and shortcuts (Wolbers & Hegarty, 2010). This kind of flexible internal representation of large-scale environments is often called a cognitive map (O'Keefe & Nadel, 1978; Tolman, 1948). Whether people create cognitive maps may depend on environmental characteristics, navigational demands, and individual and cultural differences (Peer, Brunec, Newcombe, & Epstein, 2021).

Adults show great variation in their abilities, strategies, and preference to form cognitive maps (Fields & Shelton, 2006; Hegarty, Montello, Richardson, Ishikawa, & Lovelace, 2006; Ishikawa & Montello, 2006; Weisberg & Newcombe, 2016, 2018). For example, studies using the Virtual Silcton navigation paradigm (Schinazi, Nardi, Newcombe, Shipley, & Epstein, 2013) have repeatedly found three groups. As we detail later in the Method section, this paradigm requires participants to learn locations of buildings by "walking" along two unconnected main routes in a virtual environment (VE) (cf. Fig. 1, solid lines). Next, participants are asked to walk along two new connecting routes that

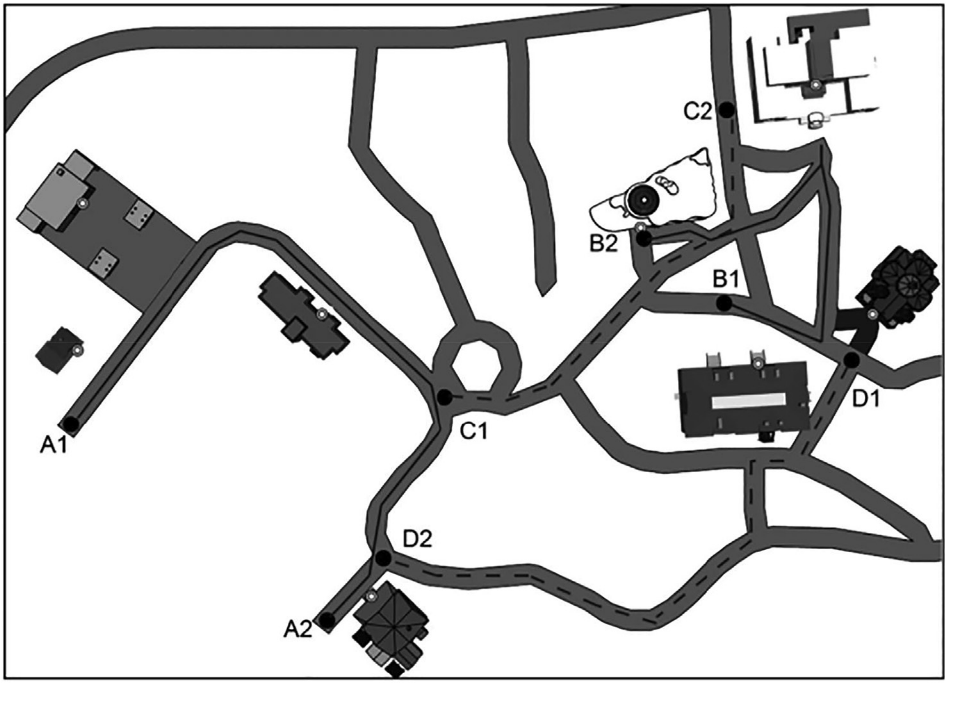


**Fig. 1.** An aerial view map of Virtual Silcton virtual environment (VE). The two main routes of the VE are shown in solid lines (A and B), and the two connecting routes are shown in dashed lines (C and D). The start and end points along each route are indicated by letter–number labeling. Participants walked from Point 1 to Point 2 and then back to Point 1 for each route. The presentation of the main routes was counterbalanced (A or B first), as was the presentation of connecting routes (C or D first).

do not have new buildings and serve as connections between the two separate main routes they learned before (cf. Fig. 1, dashed lines). This learning phase with exploration through connecting routes provides the opportunity to build a cognitive map. If a participant is placed on Main Route A and is asked to point to a building from Main Route A, this is called within-route pointing, whereas if a participant is on Main Route A and is asked to point to a building on Main Route B, this is called between-route pointing. Some people are accurate at pointing to locations both within and between routes (i.e., integrators), some are accurate at pointing within routes but perform poorly between routes (i.e., non-integrators), and some perform poorly at pointing in either situation (i.e., imprecise) (Weisberg & Newcombe, 2016; Weisberg, Schinazi, Newcombe, Shipley, & Epstein, 2014). Performance may reflect a combination of ability, strategy, and motivation. Individual differences in anxiety around navigation, everyday navigation behaviors, and personality may also affect performance (He & Hegarty, 2020).

There are several studies of the relation between spatial abilities and cognitive mapping performance. In particular, large-scale navigation performance correlates with two small-scale spatial skills—mental rotation (MR) and perspective taking (PT)—in both adults (e.g., Kozhevnikov, Motes, Rasch, & Blajenkova, 2006; Weisberg & Newcombe, 2016) and children (e.g., Nazareth, Weisberg, Margulis, & Newcombe, 2018). Like navigation, MR and PT show a wide range of individual differences in performance (Brucato, Frick, Pichelmann, Nazareth, & Newcombe, 2022; Khooshabeh, Hegarty, & Shipley, 2013), and they develop over time. Nazareth et al. (2018) found that PT accounts for more variance in navigation behavior than MR, perhaps because MR involves intrinsic transformation of objects, whereas PT involves extrinsic transformation among object relations (Newcombe & Shipley, 2015). This idea is supported by data from neuroimaging studies showing that the two skills engage different neural substrates, with PT but not MR engaging regions associated with navigation, such as the parieto-occipital sulcus/retrosplenial cortex and the hippocampus (Lambrey, Doeller, Berthoz, & Burgess, 2011).

In terms of normative development, the ability to form cognitive maps seems to take more than a decade to develop fully. Important navigational skills like place learning are intact by 2 years of age, followed by development of more advanced skills like encoding and integrating multisensory spatial cues and recognizing places from various perspectives across 3 to 10 years of age (Newcombe, 2019). However, the period of late childhood and early adolescence is pivotal for the development of spatial skills. Many skills related to large-scale navigation do not mature until early adolescence: using distal cues (Buckley, Haselgrove, & Smith, 2015), perspective taking (Vander Heyden, Huizinga, Raijmakers, & Jolles, 2017), taking detours and shortcuts (Broadbent, Farran, & Tolmie, 2014; Burles et al., 2020; Murias, Slone, Tariq, & Iaria, 2019), and map use (Liben, Myers, Christensen, & Bower, 2013). Nazareth et al. (2018), using Virtual Silcton with children aged 8 to 16 years, found that within-route and between-route pointing errors decreased with age and that navigational skills reached adult levels around 12 years of age. By 12 years, it was also possible to group children into the same three types of navigators observed in adults (i.e., imprecise navigators, non-integrators, and integrators).

Although cross-sectional work has provided a foundation for understanding individual differences and the normative development of cognitive mapping, a longitudinal design is necessary to address an important issue concerning individual differences, namely the age at which they become more stable over time. Following up on Nazareth et al.'s (2018) original cross-sectional study, the current longitudinal research had several aims. First, we aimed to replicate prior findings using cross-sectional samples in a longitudinal design. We hypothesized that, as in the cross-sectional study, overall performance would level off around 12 years of age and that within-route pointing performance would improve faster with age than between-route pointing performance. Second, we aimed to evaluate whether longitudinal stability increased at 12 years of age as well. Third, we aimed to investigate whether MR and PT were mechanisms supporting gains in navigation proficiency given that these spatial skills also develop with age, show considerable individual differences, and correlate with navigation ability. We hypothesized that PT skills, but not MR skills, at Timepoint 1 would significantly predict VE performance at Timepoint 2. Fourth, we aimed to understand whether parents' spatial skills relate to their children's change in performance over time when controlling for parents' general intelligence. A recent meta-analysis of 37 twin studies demonstrated that spatial abilities such as MR are highly heritable (King, Katz, Thompson, & Macnamara, 2019), although neither PT nor navigation abilities were assessed in King et al.'s (2019) meta-analysis. Parents' PT performance may predict children's PT performance, which in turn may support children's development of PT given that parents with increased spatial skills may play more spatial games (e.g., puzzles, blocks) and/or use more spatial language around their children, which is known to support the proficiency of these abilities (Pruden, Levine, & Huttenlocher, 2011).

## Method

### *Participants*

Participants were recruited through a database at the Temple University Infant and Child Laboratory. The sample at Timepoint 1 included 105 participants aged 8 to 16 years ($M$ = 12.17 years, $SD$ = 2.54; 54 male and 51 female). Cross-sectional analyses from Timepoint 1 were previously reported in Nazareth et al. (2018). In the current study, we report on longitudinal data of 50 participants ($M_{age}$ = 14.92 years, $SD$ = 2.43; 24 male and 26 female; see Tables 1 and 2) who returned for a second round of testing about 3 years after Timepoint 1 ($M$ = 3.36 years, $SD$ = 0.57, Min = 1.92, Max = 4.43). There were no inclusion or exclusion criteria for recruitment at Timepoint 1; however, participants were ineligible to return for Timepoint 2 if they were licensed or permit drivers. In addition, one parent of each child was asked to participate in a shortened protocol to assess whether parent abilities on psychometric tasks were related to longitudinal performance of children. A total of 44 parents participated, and 2 data points were missing due to computer error. Partial missing data due to computer error for children and adults was dealt with using pairwise deletion to ensure the maximum sample size for each analysis.

### *Materials*

The experiment was administered on two Windows 7 64-bit computers. Participants were randomly assigned to a testing computer. One of the computers had an Intel Core 2 Quad CPU at 2.66 GHz and an NVIDIA Quadro FX 1800 graphics card; the second computer had an Intel Core i5 CPU at 3.50 GHz and an NVIDIA GeForce GT 610 video card. The VE was displayed on a 40 × 62-cm LCD monitor with a refresh rate of 60 Hz and a resolution of 1920 × 1200.

### *VE navigation paradigm: Virtual Silcton*

Virtual Silcton is a desktop-based navigation paradigm based on a real-world college campus (Schinazi et al., 2013; Weisberg et al., 2014). The VE has two main routes with four unique target buildings on each for a total of eight target buildings (see Fig. 1). Between these two main routes were

**Table 1**
Total numbers of participants by age and gender.

| Age (years) | Timepoint 1 | | | Timepoint 2 | | |
|---|---|---|---|---|---|---|
| | Male | Female | Total | Male | Female | Total |
| 8 | 2 | 4 | 6 | – | – | – |
| 9 | 4 | 3 | 7 | – | – | – |
| 10 | 3 | 7 | 10 | – | – | – |
| 11 | 6 | 0 | 6 | 1 | 2 | 3 |
| 12 | 3 | 2 | 5 | 6 | 5 | 11 |
| 13 | 4 | 4 | 8 | 3 | 6 | 9 |
| 14 | 1 | 3 | 4 | 2 | 1 | 3 |
| 15 | 1 | 3 | 4 | 5 | 2 | 7 |
| 16 | – | – | – | 2 | 0 | 2 |
| 17 | – | – | – | 4 | 5 | 9 |
| 18 | – | – | – | 1 | 3 | 4 |
| 19 | – | – | – | 0 | 2 | 2 |
| Total | 24 | 26 | 50 | 24 | 26 | 50 |

**Table 2**
Total numbers of participants by median-split age group and gender.

| Age group | Male | Female | Total |
|---|---|---|---|
| Lower (Timepoint 1 age = 8–11 years) | 15 | 14 | 29 |
| Upper (Timepoint 1 age = 12–16 years) | 9 | 12 | 21 |
| Total | 24 | 26 | 50 |

also two connecting routes. During the learning phase, participants were first instructed to learn the names and locations of all eight target buildings by virtually walking along each main route indicated by red arrows. Participants used the arrow keys on a computer keyboard to move along the virtual paths and used a computer mouse to look 360° around the VE. Participants were told to pay attention to the front door of each building because that was the specific spot they would be asked to point to later in the experiment. Target buildings in the VE were indicated by a blue gem hovering near the names of the target buildings. The main route that was presented first was counterbalanced between participants. They walked from the start of each route to the end and then back to the start; thus, each route was completed twice before moving on to the next route. Participants were told not to veer off the path marked by red arrows but that they could take as much time as they liked on each route.

Immediately after learning the four target buildings on each main route, participants learned how the eight target buildings were connected by walking down two connecting routes. Before starting the two connecting routes, participants were told that these paths would "connect" or "go in between" the first two paths they had just learned. The experimenter noted that these connecting routes would not include any new buildings for participants to remember and that instead their role was to help participants understand how the buildings related to one another. Similar to the main routes, the connecting routes were counterbalanced between participants; however, they were always presented after the main routes. Participants were reminded to stay on the route marked by red arrows.

The learning phase was untimed, and participants could take as long as they needed on each of the routes. There was no additional learning criterion before participants moved to the testing phase. During the testing phase, participants completed two spatial tasks—a pointing task and a model-building task—that tested their ability to create accurate and integrated representations of the VE. In addition to the two spatial tasks, participants completed a cued building recognition task.

*Pointing task.* In the pointing task, participants were randomly located adjacent to the first target building of one of the two main routes and were prompted to point in the direction of each of the remaining seven buildings using a virtual crosshair (see Fig. 2). Using the computer mouse, participants could rotate 360° in the horizontal plane. They were instructed to point the crosshair to the front door of each target building and to click once to record their answer using the mouse. Clicking the mouse also advanced to the next trial, changing the target building in the prompt at the top of the screen. Once participants pointed to the seven target buildings, they were relocated to the next target building and this process was repeated for each of the eight buildings in the VE. A pointing error score for each participant was calculated based on the absolute value of the participant's answer minus the correct answer. If that value exceeded 180°, we corrected it by subtracting the value from 360°. A within-route error score was calculated for trials in which the target building was on the same route as that of the participant. A between-route error score was calculated for trials in which the target building was on a different main route than that of the participant. Therefore, performance on the pointing task was subdivided into within-route and between-route pointing performances based on the position of the target building in relation to the participant's pointing location in the VE. This resulted in a total of 56 pointing trials—24 within-route trials and 32 between-route trials.

*Model-building task.* In the model-building task, participants were told to make a map of the VE using a bird's-eye view inside a blank box on a computer screen. Below the box were aerial views of the eight buildings that participants could hover over with the mouse to see the front views and building names. Participants needed to drag and drop the miniature models of the eight buildings into the


**Fig. 2.** Pointing task from participants' point of view. Participants rotated a virtual crosshair 360° along the horizontal plane with a computer mouse to point in the direction of a target building.

blank box at spatial locations relative to each other in order to recreate the VE (see Fig. 3). A bidimensional regression analysis (Friedman & Kohler, 2003; Tobler, 1994) was used to calculate the $R^2$ for each participant. The $R^2$ value corrects for rotational, translational, and scale differences between

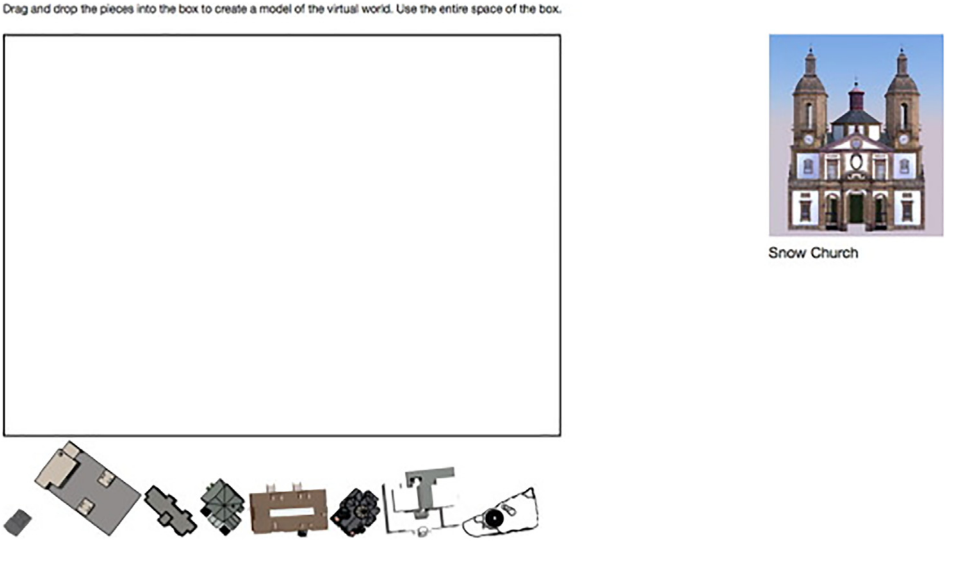


**Fig. 3.** Model-building task. The aerial view of the eight target buildings was presented at the bottom of the screen. Participants could place the computer mouse on any of the target buildings to see the front view and name of the building on the right of the screen. Participants were asked to drag and drop the eight target buildings in the empty box to represent the spatial relations of the buildings in the virtual environment.

the participant map and the actual map and indicates the remaining proportion of variance in the participant's map accounted for by the actual map. It can be interpreted as configurational accuracy (Nazareth et al., 2018).

*Building recognition task.* Participants were shown an image of each of the eight target buildings in the VE and were asked to name the building. Participants could either type the name directly into the computer or dictate it to the experimenter. They were given 1 point for each correct response, and scores could range from 0 to 8 points. A building name was counted as correct if the building was uniquely identifiable from the response.

*Psychometric measures*

*Spatial orientation test.* A revised version of the test used by Kozhevnikov and Hegarty (2001), the Spatial Orientation Test (SOT; Hegarty & Waller, 2004) tests the ability of participants to imagine different perspectives and orientations in space. In this task, participants saw an array of two-dimensional objects on a sheet of paper and were asked to imagine that they were standing at one object with a specific facing orientation. They were asked to draw an arrow from this spatial location and orientation to a third object in the array. There were 12 items, and participants were given 5 min to complete the test. The SOT error score was the average of the absolute difference in angle between the correct response and the participant's response. If that value exceeded 180°, we corrected it by subtracting the value from 360°.

*Mental rotation test.* The Mental Rotation Test (MRT; Vandenberg & Kuse, 1978; adapted by Peters et al., 1995) consists of 20 items, each made up of one target figure and 4 response items. Of the 4 response items, 2 are identical to the target figure but are presented at varying orientations. The remaining 2 items are mirror images of the target figure. Participants were asked to identify the 2 response items that were identical but rotated images of the target figure. Before beginning the task, participants were given three practice trials. If they got any of the practice problems incorrect, they reviewed their answers with the experimenter and found the right one before moving on to the actual task. Participants received 2 points for each correct response and lost 2 points for each incorrect response.

*Word reading subtest of wide range achievement test.* The word reading subtest of the Wide Range Achievement Test (WRAT; Wilkinson & Robertson, 2006) is a measure of verbal fluency/verbal intelligence that is highly correlated with the Wechsler Abbreviated Scale of Intelligence–Third Edition and the Wechsler Intelligence Scale for Children–Fourth Edition (Strauss, Sherman, & Spreen, 2006). The WRAT was used as a control measure proxy for parents' general intelligence. Parents were given a list of 55 words of increasing difficulty and were asked to pronounce them aloud. The experimenter, who was trained on the correct pronunciations ahead of time, scored the accuracy of each pronunciation. The total score was the proportion of correctly pronounced words.

*Procedure*

The procedure took approximately 1 h at each timepoint. The procedure was the same at each timepoint except that parents' participation occurred only at Timepoint 2. Participants' parents completed an informed consent form while their children completed an assent form with assistance from the experimenter if needed. First, children were taken to the testing room and guided through the learning and testing phases of the VE task. Following the VE task, they completed the MRT and SOT psychometric measures and finally the building recognition task. Following their children's participation at Timepoint 2, parents completed the MRT, SOT, and WRAT.

## Results

### Dropout effects

Means for all tasks administered at Timepoint 1 were compared for the 50 participants who returned for Timepoint 2 and the 55 who did not. There were no significant differences in mean scores for any of the variables (all *t*s < 1.50 and *p*s > .14). The male–female ratio was also the same, $\chi^2(1, N = 105) = 0.23$, $p = .635$. However, the mean age at Timepoint 1 was significantly lower for participants who returned at Timepoint 2 ($M = 11.55$ years, $SD = 2.18$) than for those who did not ($M = 12.74$ years, $SD = 2.74$), $t(102) = 2.44$, $p = .016$, reflecting the fact that older participants were more likely to be living away from home or drivers at the time of follow-up.

### Descriptive statistics and sex differences

Descriptive statistics for tasks that parents performed at Timepoint 2 are shown in Table 3. Descriptive statistics for tasks given to children at both timepoints are shown in Table 4. There was no significant difference in age between male participants ($M = 14.73$ years, $SD = 2.11$) and female participants ($M = 15.10$ years, $SD = 2.72$) at Timepoint 2, $t(48) = -0.52$, $p = .604$, $d = 0.15$, 95% confidence interval (CI) = [−0.41, 0.70]. Table 5 shows that there were no significant sex differences for any of the navigation or psychometric tasks at Timepoint 2.

### Normative development

To investigate whether performance on navigation and psychometric measures improved across timepoints, we conducted a paired-samples *t* test for each task. As can be seen in Table 6, participants significantly improved on all measures. To assess whether improvement was similar for children across the entire age range or was greater for younger children, we performed a median split to separate participants into two age groups. The lower age group included children who were 8 to 11 years old at Timepoint 1, and the upper age group included those who were 12 to 16 years old at Timepoint 1. As shown in Fig. 4 and Table 6, improvement over time was primarily driven by the lower age group. The upper age group did not significantly improve in their navigation performance across timepoints. Mean performance at each 1-year age interval for the within-route and between-route pointing data is shown in Fig. 5.

### Stability of individual differences

The longitudinal stability of each task is reported in Table 7 as the partial Pearson correlation between Timepoint 1 and Timepoint 2, removing the effect of difference in amount of time between timepoints. To determine whether stability differed across age groups, we conducted a Fisher's *z* test to compare the Pearson correlations between Timepoint 1 and Timepoint 2 of the lower age group with those of the upper age group. Correlations of between-route pointing error and the MRT at Timepoints 1 and 2 were significantly different for the upper and lower age groups. Crucially, the significant difference in stability of between-route pointing between age groups (cf. Table 7) suggests that individual differences in cognitive mapping performances stabilize around 12 years of age. In contrast,

**Table 3**
Descriptive statistics for psychometric tasks of parents at Timepoint 2.

| | *N* | Min | Max | *M* | *SD* |
|---|---|---|---|---|---|
| Spatial Orientation Test (error) | 42 | 7.25 | 136.60 | 24.54 | 23.57 |
| Mental Rotation Test | 44 | 0.00 | 23.00 | 10.09 | 6.75 |
| Wide Range Achievement Test | 43 | 49.00 | 55.00 | 52.37 | 1.98 |

**Table 4**
Descriptive statistics for psychometric and navigation tasks of children across timepoints.

| | Timepoint 1 | | | | | Timepoint 2 | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | *N* | Min | Max | *M* | *SD* | *N* | Min | Max | *M* | *SD* |
| Within route (error) | 50 | 16.24 | 80.82 | 44.27 | 16.54 | 46 | 11.46 | 64.47 | 35.68 | 14.27 |
| Between route (error) | 50 | 28.40 | 92.75 | 68.26 | 12.12 | 46 | 22.95 | 88.55 | 60.29 | 16.24 |
| Model building (total) | 49 | 0.00 | 0.76 | 0.30 | 0.22 | 48 | 0.01 | 0.94 | 0.49 | 0.26 |
| Model building (within) | 50 | 0.12 | 0.93 | 0.50 | 0.19 | 48 | 0.15 | 0.94 | 0.62 | 0.22 |
| Building recognition | 49 | 2.00 | 8.00 | 6.22 | 1.83 | 49 | 4.00 | 8.00 | 7.24 | 1.09 |
| SOT (error) | 50 | 8.58 | 106.08 | 63.52 | 28.03 | 50 | 6.42 | 109.17 | 38.91 | 31.99 |
| MRT | 47 | −24.00 | 72.00 | 26.55 | 19.80 | 48 | 6.00 | 80.00 | 38.70 | 18.77 |

*Note.* SOT, Spatial Orientation Test; MRT, Mental Rotation Test.

**Table 5**
Sex differences in children's navigation and psychometric performance at Timepoint 2.

| Task | Male | | | Female | | | *t* | *p* | *d* | 95% CI |
|---|---|---|---|---|---|---|---|---|---|---|
| | *n* | *M* | *SD* | *n* | *M* | *SD* | | | | |
| Within-route (error) | 21 | 34.93 | 13.83 | 25 | 36.31 | 14.89 | −0.32 | .749 | 0.10 | [−0.48, 0.68] |
| Between-route (error) | 21 | 61.03 | 16.82 | 25 | 59.67 | 16.06 | 0.28 | .781 | −0.08 | [−0.66, 0.50] |
| Model-building (total) | 23 | 0.46 | 0.26 | 25 | 0.50 | 0.26 | −0.55 | .587 | 0.16 | [−0.41, 0.73] |
| Model-building (within) | 23 | 0.63 | 0.23 | 25 | 0.62 | 0.21 | 0.26 | .800 | −0.08 | [−0.64, 0.49] |
| SOT (error) | 24 | 32.93 | 26.71 | 26 | 44.44 | 35.81 | −1.28 | .207 | 0.37 | [−0.20, 0.93] |
| MRT | 23 | 41.91 | 18.47 | 25 | 35.76 | 18.92 | 1.14 | .261 | −0.34 | [−0.91, 0.24] |

*Note.* CI, confidence interval; SOT, Spatial Orientation Test; MRT, Mental Rotation Test.

**Table 6**
*t*-Test results and effect sizes for children's improvement on navigation and psychometric measures over time.

| | *N*/*n* | *t* | Mean difference | *d* |
|---|---|---|---|---|
| *Overall* | | | | |
| Within route (error) | 46 | 2.97** | 7.66 [2.47, 12.86] | 0.44 [−0.15, 1.02] |
| Between route (error) | 46 | 2.99** | 8.13 [2.65, 13.61] | 0.44 [−0.15, 1.02] |
| Model building (total) | 47 | −4.00** | −0.19 [−0.28, −0.09] | 0.58 [0.00, 1.16] |
| Model building (within) | 48 | −3.72** | −0.13 [−0.20, −0.06] | 0.54 [−0.04, 1.11] |
| SOT (error) | 50 | 6.06** | 23.79 [16.79, 32.43] | 0.85 [0.31, 1.47] |
| MRT | 45 | −4.27** | −12.27 [−18.06, −6.48] | 0.64 [0.03, 1.23] |
| *Lower age group* | | | | |
| Within route (error) | 27 | 2.63* | 9.56 [2.08, 17.04] | 0.51 [−0.27, 1.27] |
| Between route (error) | 27 | 2.45* | 9.21 [1.48, 16.95] | 0.47 [−0.30, 1.23] |
| Model building (total) | 28 | −3.71** | −0.23 [−0.36, −0.10] | 0.70 [−0.07, 1.46] |
| Model building (within) | 29 | −4.12** | −0.17 [−0.26, −0.09] | 0.77 [0.00, 1.51] |
| SOT (error) | 29 | 4.91** | 27.67 [16.13, 39.21] | 0.91 [0.14, 1.67] |
| MRT | 28 | −3.84** | −16.43 [−25.20, −7.66] | 0.73 [−0.05, 1.49] |
| *Upper age group* | | | | |
| Within route (error) | 19 | 1.41 | 4.97 [−2.42, 12.35] | 0.32 [−0.59, 1.23] |
| Between route (error) | 19 | 1.67 | 6.60 [−1.68, 14.87] | 0.38 [−0.53, 1.29] |
| Model building (total) | 19 | −1.75 | −0.12 [−0.26, 0.02] | 0.40 [−0.51, 1.31] |
| Model building (within) | 19 | −1.03 | −0.06 [−0.17, 0.06] | 0.24 [−0.67, 1.13] |
| SOT (error) | 21 | 4.05** | 20.38 [9.88, 30.88] | 0.88 [−0.03, 1.77] |
| MRT | 17 | −2.53* | −5.41 [−9.95, −0.87] | 0.61 [−0.37, 1.58] |

*Note*. SOT, Spatial Orientation Test; MRT, Mental Rotation Test. The lower age group included children aged 8 to 11 years at Timepoint 1, and the upper age group included children aged 12 to 16 years at Timepoint 1. Numbers in brackets are 95% confidence intervals.
* $p < .05$.
** $p < .01$.

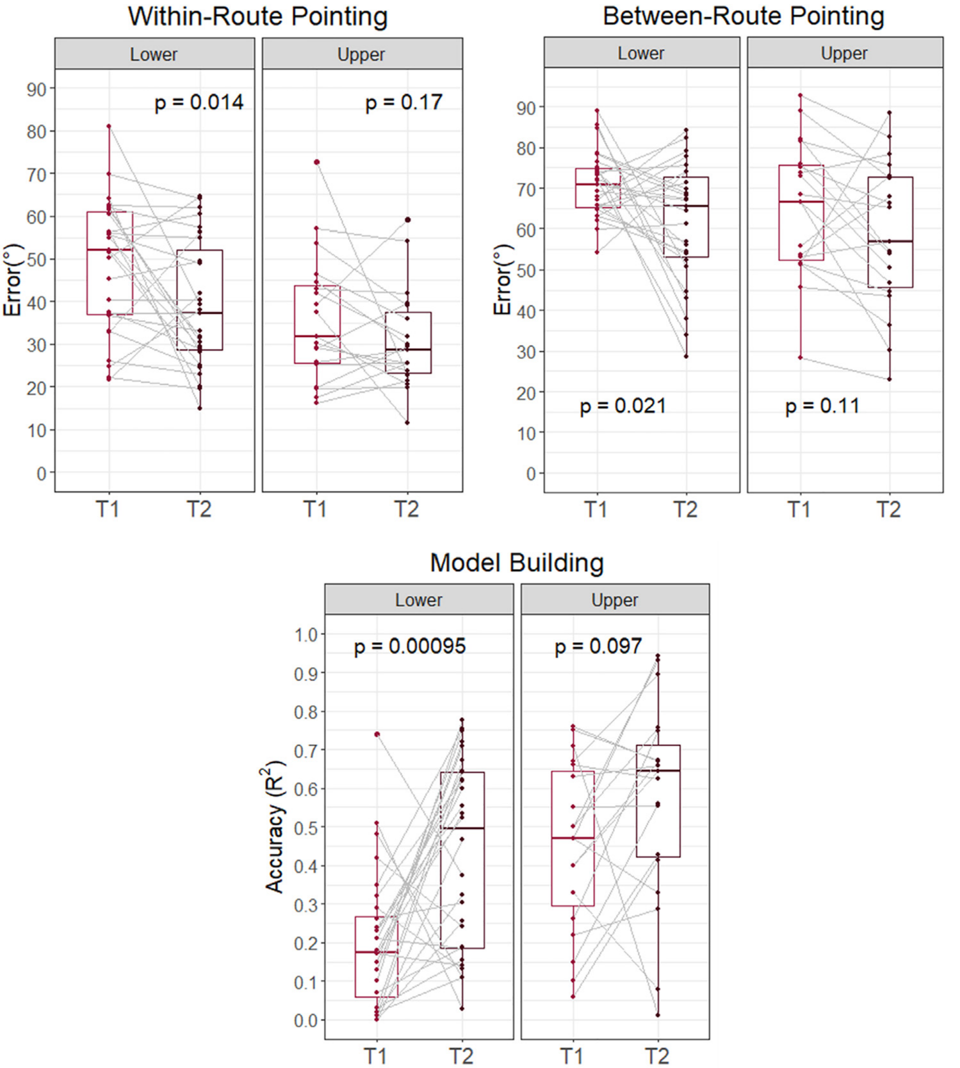


**Fig. 4.** Boxplots of improvement on navigation measures by age (upper and lower age groups). T1, Timepoint 1; T2, Timepoint 2. $N_{pointing}$ = 46; $N_{model}$ = 47.

there was no significant difference in within-route pointing between the age groups, indicating that route knowledge stabilizes before route integration, that is, before 12 years of age.

*Rate of development*

Previously, Nazareth et al. (2018), found that there was a steeper rate of improvement in within-route pointing performance as opposed to between-route pointing performance. We followed up on this finding by evaluating the difference in slopes for within-route versus between-route pointing (see Fig. 5) in the returning sample by regressing pointing error on participant age and calculating

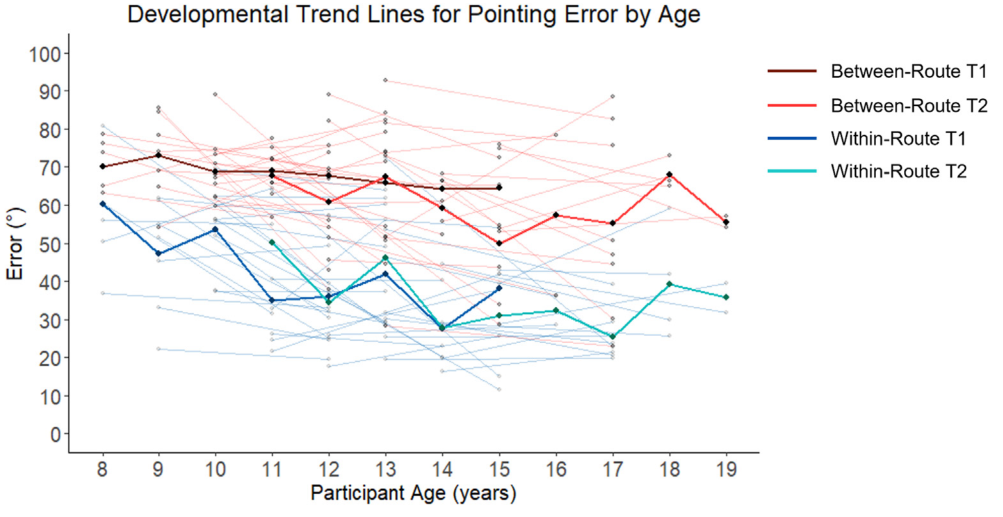


**Fig. 5.** Developmental trend lines for between-route and within-route pointing by age. T1, Timepoint 1; T2, Timepoint 2. Light-colored red and blue lines connected by gray dots represent individual participants for between-route pointing and within-route pointing, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

the interaction between age and type of pointing trials. In the regression model, the interaction term tested for the assumption of parallelism of the slopes of within-route and between-route pointing trials. Results of the regression model indicated that the slopes were not significantly different at Timepoint 1 ($\beta$ = –0.27, $p$ = .119) or at Timepoint 2 ($\beta$ = –0.11, $p$ = .473). Thus, for the participants who returned for Timepoint 2, there was no age-related difference in the rate of change for within-route and between-route pointing error. However, given that the longitudinal sample from this analysis consisted of only 46 participants, we might not have had sufficient power to detect this particular effect, which was found previously with a much larger sample.

## *Predictors of change in navigation ability*

### *Timepoint 1 measures*

We conducted a multiple regression analysis to assess whether performance on within-route pointing, between-route pointing, model building, SOT, or MRT at Timepoint 1 predicted variance in the change of performance on navigation measures across timepoints (see Table 8). We controlled for the difference of time between timepoints by including this as our first variable in each regression.

**Table 7**
Longitudinal stability of tasks by age group when controlling for differences in time between timepoints.

| | Lower age group | | | Upper age group | | | |
|---|---|---|---|---|---|---|---|
| Task | *r* | *p* | *n* | *r* | *p* | *n* | *z* |
| Within route (error) | .23 | .262 | 27 | .51 | .032 | 19 | 1.00 |
| Between route (error) | –.42 | .031 | 27 | .52 | .026 | 19 | 3.21** |
| Model building (total) | –.19 | .342 | 28 | .19 | .460 | 19 | 1.19 |
| Model building (within) | .42 | .026 | 29 | .09 | .734 | 19 | –1.13 |
| Building recognition | .13 | .498 | 29 | .32 | .198 | 19 | 0.61 |
| SOT (error) | .55 | .002 | 29 | .48 | .032 | 21 | –0.33 |
| MRT | .20 | .325 | 28 | .80 | <.001 | 17 | 2.68** |

*Note*, SOT, Spatial Orientation Test; MRT, Mental Rotation Test. The lower age group included children aged 8 to 11 years at Timepoint 1, and the upper age group included children aged 12 to 16 years at Timepoint 1.
** $p < .01$.

When looking across both age groups, each navigation task at Timepoint 1 significantly predicted change in performance for that same task at Timepoint 2 (*ps* < .05) but not the others except for within-route pointing at Timepoint 1, which also predicted change in between-route pointing over time ($B$ = 0.44, $p$ < .001).

We then conducted the same analysis split by age group. For participants in the lower age group (i.e., children who were under 12 years at Timepoint 1), each navigation task at Timepoint 1 significantly predicted change in performance for that same task at Timepoint 2 (*ps* < .05) but not the others. For participants in the upper age group (i.e., children who were 12 years or over at Timepoint 1), between-route pointing error at Timepoint 1 was the only significant predictor, predicting change in between-route pointing error over time ($B$ = −0.75, $p$ = .037).

*Parents' small-scale spatial skills*

To test whether parent small-scale spatial skills were related to children's performance on the psychometric and navigation tasks, we conducted partial Pearson correlation analysis of parent SOT and MRT performance with all tasks from Timepoint 1, Timepoint 2, and the difference in performance between timepoints, removing the effect of parent WRAT performance (see Table A1 in Appendix). All correlations were nonsignificant (*rs* < .25, *ps* > .05).

## Discussion

The current longitudinal study followed up on recent cross-sectional work and replicated several findings on normative development. First, we found that children in the lower age group who were 8 to 11 years old at Timepoint 1 significantly improved on all navigation measures by Timepoint 2. In contrast, children in the upper age group who were 12 to 16 years old at Timepoint 1 did not show significant differences in performance by Timepoint 2. In addition, the longitudinal stability of between-route pointing across timepoints was different between the age groups, showing a negative association of performance between timepoints for the lower age group but a positive association for the upper age group. Together, these findings support the idea that large-scale spatial navigation abilities continue to develop until around 12 years of age when the onset of individual differences stabilizes.

Next, we followed up on the cross-sectional finding of Nazareth et al. (2018) that age-related improvement on within-route pointing occurs earlier and at a faster rate than between-route pointing.

**Table 8**
Standardized regression beta weights for Timepoint 1 navigation and psychometric tasks as predictors for change in performance on navigation tasks: Change scores.

| | Timepoint 1 predictors | | | | |
|---|---|---|---|---|---|
| | Within route | Between route | Model building | SOT | MRT |
| | *Overall* | | | | |
| Within route (error) | −0.732 (0.188)** | 0.047 (0.155) | 0.005 (0.173) | −0.002 (0.189) | 0.231 (0.186) |
| Between route (error) | 0.440 (0.200)* | −0.996 (0.165)*** | −0.187 (0.184) | −0.022 (0.200) | 0.249 (0.198) |
| Model building (total) | −0.060 (0.223) | −0.007 (0.185) | −0.980 (0.206)*** | −0.142 (0.204) | 0.021 (0.219) |
| | *Lower age group* | | | | |
| Within route (error) | −0.923 (0.291)** | −0.416 (0.373) | −0.122 (0.337) | 0.020 (0.306) | 0.028 (0.326) |
| Between route (error) | 0.296 (0.233) | −1.460 (0.299)*** | −0.119 (0.270) | −0.170 (0.245) | 0.146 (0.261) |
| Model building (total) | −0.185 (0.276) | 0.153 (0.346) | −1.385 (0.316)*** | 0.057 (0.246) | −0.152 (0.316) |
| | *Upper age group* | | | | |
| Within route (error) | −0.491 (0.220) | 0.191 (0.138) | −0.082 (0.230) | −0.307 (0.199) | −0.199 (0.310) |
| Between route (error) | 0.776 (0.485) | −0.748 (0.305)* | 0.123 (0.507) | 0.061 (0.439) | 0.620 (0.684) |
| Model building (total) | −0.003 (0.528) | −0.056 (0.332) | −1.114 (0.552) | −0.570 (0.478) | −0.417 (0.744) |

*Note.* SOT, Spatial Orientation Test; MRT, Mental Rotation Test. The lower age group included children aged 8 to 11 years at Timepoint 1, and the upper age group included children aged 12 to 16 years at Timepoint 1. Change scores are Timepoint 2 scores – Timepoint 1 scores. Standard errors of standardized regression beta weights are in parentheses.

* $p$ < .05.

** $p$ < .01.

*** $p$ < .005.

We found that the longitudinal stability of within-route pointing was not significantly different between age groups, but that of between-route pointing was. Thus, this finding supports the idea that age-related performance on within-route pointing stabilizes earlier than that on between-route pointing. However, we did not find that there was a significant difference in the rate of improvement between within-route and between-route pointing scores in our reduced returning sample. This null result should be considered in the context of a decrease in sample size from the original study given that less than half of those who participated at Timepoint 1 returned and had pointing data to be analyzed at Timepoint 2. Thus, we might not have had sufficient power to detect this particular effect.

Relatedly, in the current study we found that when looking at all participants together, collapsed across age group, within-route pointing performance at Timepoint 1 predicted change in both within-route and between-route pointing over time. This suggests that knowledge about route representations builds on later route integration ability. This result suggests some support for the model proposed by Siegel and White (1975) that development of route-based knowledge precedes that of survey-based knowledge; however, our findings suggest a more parallel development than strictly sequential development of these abilities given that within-route pointing continued to improve in tandem with between-route pointing.

In addition to replicating findings on normative development, the current study leveraged a longitudinal approach to probe potential predictors of individual differences in the development of cognitive mapping ability. PT has previously been associated with navigation performance in both behavioral studies (Kozhevnikov et al., 2006; Liben et al., 2013; Schinazi et al., 2013) and neuroimaging studies (Lambrey et al., 2011) and was found to be a key factor in development of navigation ability in Nazareth et al.'s (2018) cross-sectional study. However, in the current longitudinal study, we found that neither PT nor MR was a significant predictor of change in navigation performance over time. Our findings suggest that researchers may need to look beyond small-scale spatial skills to identify factors that contribute to the development of navigation ability. For example, a recent study by He and Hegarty (2020) suggested that in adults small-scale spatial skills, but also a variety of other factors, may affect navigation proficiency, including level of anxiety around navigation, tendencies for exploration, and Global Positioning System (GPS) dependency. In addition to, or in combination with, these additional variables not assessed in the current study, the type of psychometric tasks administered may also contribute to the null finding. Although the SOT has previously been used in studies looking at the unique predictive contributions of PT to navigation, Brucato et al. (2022) found that the SOT shows less divergent validity from MR than from other PT tasks. Future studies may consider administering different or multiple types of PT tasks to elucidate distinct contributions of PT to navigation.

Given previous work on parents' role in the development of small-scale spatial skills (e.g., Pruden et al., 2011), we predicted that parents' spatial skills would predict children's PT ability and in turn their navigation abilities. However, we found no relationship between parents' performance and their children's performance. This result is somewhat surprising given King et al.'s (2019) meta-analysis of twin studies, which suggests that mental rotation abilities are highly heritable. However, their study reported that for children under 15 years old, shared environmental factors among twins showed high amounts of influence on spatial ability. Thus, it may be that for younger children environmental factors, such as access to games that produce spatial language between parents and children, are more predictive of later ability than parents' spatial ability alone. This leaves an open question for future studies about how frequency of spatial language among parents and children may affect not only small-scale spatial skills but also large-scale navigation ability. In addition, the current study included data of small-scale spatial skills from only one parent. Thus, a potential explanation for lack of association between parents' and children's spatial skills in the current study may be that another parent or caregiver may be providing spatial scaffolding and experiences to participants that were not recorded in our current sample. Of additional note, the natural ranges of performance on small-scale spatial tasks for parents were smaller than those for children in our current sample, which may have also contributed to lack of association between parents' and children's performance.

Regarding sex differences, we found no differences in performance on navigation or psychometric tasks between male and female children. These results are similar to reports from Nazareth et al. (2018), who found no differences in performance between sexes on the SOT, between-route pointing, or model building. A recent meta-analysis of sex differences in navigation ability suggested that male participants tend to outperform female participants on navigation tasks but that this effect was much smaller for studies with children under 13 years of age (Nazareth, Huang, Voyer, & Newcombe, 2019). Nazareth et al. (2019) highlighted the need for more life-span developmental research on spatial navigation to further establish the effect sizes of sex differences, and the current study contributes to this call.

The current study has some limitations. First, we used a desktop VE instead of observing real-life large-scale navigation. Although this offers several benefits in terms of testing convenience, it also has the disadvantage of loss of vestibular information (Hegarty et al., 2006; Richardson, Montello, & Hegarty, 1999; Wiener-Vacher, Hamilton, & Wiener, 2013; Yoder & Taube, 2014) that can contribute to navigation performance, especially for younger children. Second, the current study did not include information about participants' experience with video games. Male and female participants within each age group may have different levels of experience with video games, which in turn may influence their familiarity and performance in a VE (Feng, Spence, & Pratt, 2007; Subrahmanyam & Greenfield, 1994; Terlecki & Newcombe, 2005). Finally, the MR and PT measures were chosen to measure a large age range and might not have been maximally age appropriate for the youngest children in the study. However, the researchers took the utmost care to ensure that even the youngest children understood each task well and demonstrated comprehension through sample problems before moving to test items.

To conclude, the current study fills a gap in the literature on the development of cognitive maps by replicating cross-sectional findings via a longitudinal design and investigating causal mechanisms of improvement over time. First, we replicated findings on the normative developmental trajectories of navigation skills in individuals aged 8 to 19 years and demonstrated that children's route representation develops earlier than, but in tandem with, route integration. Second, we showed that children continue to establish their navigation abilities until around 12 years of age when adult-level individual differences begin to stabilize. Third, we found that neither children's small-scale spatial skills nor those of their parents predict change in cognitive mapping ability over time. Future work should turn to additional predictive variables such as exploration tendencies and navigation anxiety.

## Acknowledgments

This work was supported by the National Science Foundation (EHR 1660996).

## Appendix

Table A1

**Table A1**
Correlations between children's and parents' performance on all tasks across timepoints.

| | Parent SOT | | | Parent MRT | | |
|---|---|---|---|---|---|---|
| Child measure | T1 | T2 | Change | T1 | T2 | Change |
| Within route (error) | .12 | −.12 | −.21 | .08 | .12 | .02 |
| Between route (error) | .19 | −.05 | −.18 | −.07 | −.24 | −.17 |
| Model building (total) | −.19 | −.25 | −.09 | .01 | −.12 | −.11 |
| Model building (within) | .05 | .09 | .03 | −.14 | .00 | .13 |
| SOT (error) | .22 | .19 | −.03 | −.06 | −.20 | −.17 |
| MRT | −.09 | −.02 | .08 | .06 | .15 | .06 |

*Note.* SOT, Spatial Orientation Test; MRT, Mental Rotation Test; T1, Timepoint 1; T2, Timepoint 2. Values are partial correlation coefficients between children's and parents' scores, removing the effect of parent WRAT performance. No correlations were significant (*ps* > .05). Change scores are Timepoint 2 scores − Timepoint 1 scores.

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