Variables Involved in Selective Sustained Attention Development: Advances in Measurement

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Abstract

Selective sustained attention (SSA) is an important cognitive process that enables everyday functioning and task performance by allowing us to: 1) choose components of our environment to process at the exclusion of others and 2) maintain focus on those components over time. Although SSA is known to undergo rapid and marked changes during the preschool and early primary school children years, there has been a paucity of behavioral data on these years of development due to a lack of child-appropriate testing paradigms. TrackIt is a paradigm that was recently developed to fill the previously existing measurement gap for SSA in these years. In this study, we analyzed errors that children (aged 3-7) make when performing TrackIt, to better understand what factors drive improvement in their performance over age. In addition, we manipulated parameters within TrackIt to place varying levels of demand on children's SSA, and measured behavioral performance over age, with the goal of measuring and characterizing developmental trends during these years. Since TrackIt is still a recent paradigm, our results also help suggest appropriate parameter settings for calibrating the task to different age groups.

Keywords: selective sustained attention; TrackIt

Introduction

Selective sustained attention (SSA) is an important cognitive process that enables everyday functioning and task performance by allowing us to: 1) choose components of our environment to process at the exclusion of others and 2) maintain focus on those components over time. SSA is known to rely on both endogenous factors (e.g., internal goals) as well as exogenous factors (e.g., stimulus salience) (O'Connor & Manley, 2004) -- studying specifically how these factors interact and work together in guiding attention contributes to a growing understanding of SSA's mechanisms. Task paradigms that allow simultaneous investigation of both exogenous and endogenous factors of SSA have been available for adults and infants but not for preschool and early primary school children (~3-7 years) until recently (for review, see Fisher & Kloos, 2016). These years are particularly important from a research standpoint because data from infants and adults suggests that SSA develops significantly during these intermediate years (Oakes, Kannass, & Shaddy, 2002). TrackIt, a paradigm developed specifically to fill this measurement gap, is designed to be appropriately challenging for a range of developmental years including the preschool years, with varying parameters for adjustment of difficulty across ages (Fisher et al., 2013).

Prior studies with TrackIt demonstrated that children improve on the task between 3 and 5 years of age (Fisher et al., 2013, Erickson et al., 2015), consistent with the overall developmental pattern of improvement in SSA with age. In order to investigate this improvement more closely, the current study looked at 1) what factors tend to drive the failures (errors), and what, of those, consequently improve to drive the overall performance improvement (see "Factors driving improvement" below), and 2) what the behavioral trajectories representing this improvement look like across an expanded age range. To delve into this issue, we manipulated parameters of TrackIt to place varying levels of demand on children's selective sustained attention to achieve a coarse mapping of behavioral performance in several parameter combinations over ages 3 to 7. In contrast to prior studies using TrackIt that focused on the analysis of correct responses (Fisher et al., 2013; Erickson et al., 2015), this study also examined the patterns of errors as a function of task difficulty and age.

Factors Driving Improvement

This study introduces a new addition to the TrackIt program: error analysis. This functionality (a software update that is now part of the TrackIt program that is freely available to interested researchers) adds, to the behavioral output, information on the types of errors that participants make. Analyzing the types of errors that children make over development may provide greater insight into what factors constitute the overall improvements that we see in children's SSA performance. For example, some error types help to distinguish between behavioral errors due to failure of SSA and those due to insufficient visuo-spatial resolution. Also, finding that a significant proportion of errors can be related to failure of SSA would help validate TrackIt as a task assessing attention. Thus, the first goal of this study was to present preliminary analyses of error type breakdown over age and difficulty.

Behavioral Trajectories

Mapping out age-related changes in performance within the multi-dimensional parametric space of variables (i.e., number of distractors, grid size, speed of objects, type of distractors) involved in visual attention serves two important purposes: 1) it begins to fill in the empirical gap in characterizing children's visual SSA development within a single consistent measurement framework, and 2) it suggests initial parameter selection ranges for age groups, to guide researchers using TrackIt (Doebel et al., 2015). Hence, the second goal of this study is to present preliminary findings on parameter space mappings.

Method

Participants

Participants were 144 typically developing children (71 female, M_{age}= 5.08 years) recruited from local preschools, day care centers, and elementary schools in Pittsburgh, PA. See Table 2 below for a breakdown of participant age statistics.

Materials and Apparatus

Stimuli were presented on a Lenovo touchscreen laptop with physical screen dimensions 19.1 cm x 34.2 cm and pixel dimensions 1920x1080 pixels. Participants were seated at a desk facing the screen with their heads about 2 feet away from the screen.

TrackIt Task

In this task (freely available for download at http://www.psy.cmu.edu/~trackit/), participants were asked to visually track a single target object as it moved on a grid among moving distractor objects. For each trial, the target and distractor objects were randomly picked without replacement from a set of unique objects spanning 9 different shapes with 9 different color possibilities (81 objects in total).[1] See Figure 1 for examples.

At the beginning of each trial, the objects appeared on the grid, centered in distinct grid cells, and the target object was indicated by a red circle around it. The initial positions of the objects were randomized. The experimenter started each trial with a button press after ensuring the participant was ready to begin.

Upon starting the trial, the red circle disappeared, and the objects began to move in linear trajectories from grid cell to grid cell at a constant speed. At the end of each trial, all objects disappeared from the screen, and the participants were asked to indicate with their finger (on the touch screen) which grid cell the target object was last in before it disappeared.

The sequence of positions in the path of each objects was randomized, with one restriction for just the target: the target had to be in the center of a grid cell at the end of a trial, to reduce ambiguity for the participant in determining its final location. Due to this restriction, the length of trials was not fixed, but varied slightly from trial to trial (to allow the target to reach the center of a grid cell. The minimum trial length was set to 10 seconds. The parameters -- grid size, number of distractors, and speed of objects in pixels per second -- were determined from prior testing in TrackIt with a separate group of 3- to 5-year old children (Fisher et al., 2013), and organized according to participant age and difficulty level as seen in Table 1. Object motion display was set to 30 frames per second.

Table 1: TrackIt parameter combination used in each difficulty level.

Difficulty	Age Group (years)	Grid Size	# of Distractors	Object Speed (pix/s)
Level 1	3-5	4x4	4	500
Level 2	4-6	6x6	6	500
Level 3	7	6x6	8	800

Note: pix/s = pixels/second.

We assessed three different difficulty levels, administered to different age groups, as shown in Table 1. Separate groups of participants were tested in each difficulty level. The sample size per age and difficulty level is presented in Table 2. It should be noted that, ultimately, we aim to obtain a large-scale representative sample of

[1]Children also participated in a homogeneous condition, in which all distractors are identical (but distinct from the target). This condition is designed to require less SSA because target tracking is supported exogenously by increased salience of the target. We did not analyze this condition as distinguishing exogenous vs. endogenous effects was not of interest for this study.

Table 2: Sample sizes and age statistics of each age group, for each difficulty level

Age Group (years)	Difficulty Level 1 n/m/f	Difficulty Level 1 Age Mean (Std)	Difficulty Level 2 n/m/f	Difficulty Level 2 Age Mean (Std)	Difficulty Level 3 n/m/f	Difficulty Level 3 Age Mean (Std)
3	25/13/12	3.64 (0.21)	-	-	-	-
4	17/9/8	4.64 (0.27)	19/6/13	4.69 (0.22)	-	-
5	26/14/12	5.38 (0.23)	41/19/22	5.43 (0.27)	-	-
6	-	-	6/4/2	6.34 (0.25)	-	-
7	-	-	-	-	10/8/2	7.27 (0.16)

Note: n/m/f = sample size/# male/# female.

participants at each age and difficulty level; the present paper reports the initial findings from this study.

Memory Check At the conclusion of each trial, children were presented with 4 shapes that could have served as target objects in this task (one of which was actually the target) and asked to point to the shape they had been tracking (see Figure 1). The responses to memory check questions were recorded by the children's touch screen responses. The memory checks were introduced to help discriminate between two possible reasons why a participant may fail to correctly report the location where the target object disappears. The first possibility is that encoding of the identity of the target object may be insufficiently strong to persist through an entire trial – this would indicate an encoding failure. The second possibility is that a child may track distractors for a part of the trial despite remembering which object was supposed to be watched – this would indicate the failure of selective sustained attention. The target was colored as in the trial, while the remaining 3 shapes and their colors were sampled without replacement from the remaining 8 shapes and colors.

Design and Procedure

The experimenter administered the TrackIt task to participants in a quiet room or hallway. At the beginning of the task, participants were told that: 1) the objects will start moving around the grid when the experimenter presses a button; 2) the goal is to follow the target object with their eyes; 3) at some point the objects will suddenly disappear, and their job is to point to where the target object was when it disappeared. Each trial was followed by a baseline screen displaying a smiley face, a memory check screen, and a second smiley face baseline (in that order). Participants were told that the smile did not indicate a correct answer and rather meant we were happy they were playing our game. See Figure 1 for a diagram of the task sequence.

Participants completed 11 trials of the task. The first trial was a practice trial and was completed with assistance from the experimenter who traced the moving target with their index finger. The first trial was accordingly omitted from analysis. Participants were then told that they would need to complete the rest of the task by themselves, tracking the target with their eyes only.

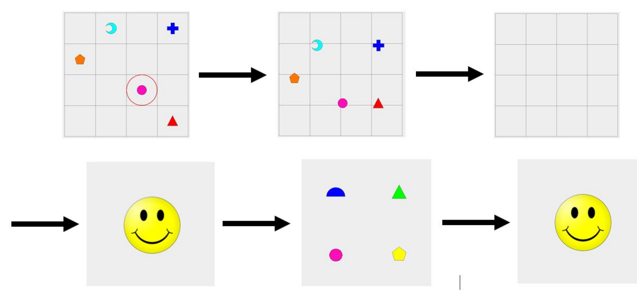

Figure 1. The TrackIt task pipeline. A single trial, followed by smiley face, memory check, and smiley face.

Error Analysis Next, we were interested in better understanding what types of tracking errors participants were making. Tracking errors were any answers in the main TrackIt task that weren't the correct cell that the target ended in. Tracking errors were thus further classified based on the incorrect grid cell response indicated by the participant, in relation to the final positions of the target and distractors on the grid. Specifically, in addition to a correct response, we considered 5 types of errors:

Spatial Resolution: The response was a cell adjacent to the correct grid cell, but was not also adjacent to a distractor.

Distractor: The response was a cell that contained a distractor.

Distractor Spatial Resolution: The response was a cell that did not contain a distractor, was adjacent to a cell that contained a distractor, and was not also adjacent to the correct grid cell.

Uncategorizable: The response was a cell that did not contain a distractor, and was adjacent to both the correct grid cell and a cell that contained a distractor.

Other: None of the above. That is, the response was a cell that did not contain a distractor, and was adjacent to neither the correct grid cell, nor a cell that contained a distractor.

In the above, "adjacent" cells are defined as those within one horizontal, vertical, or diagonal step of a given cell. (Cells are not considered adjacent to themselves.) For example, corner cells have 3 adjacent cells, edge cells have 5 adjacent cells, and other cells have 8 adjacent cells.

Note that finding that a significant proportion of errors are distractor-related errors (distractor, distractor spatial resolution, or uncategorizable) would help to validate TrackIt as a task assessing attention; if we find that kids make many spatial resolution errors, it may indicate that the performance is limited by kids' visuo-spatial acuity. In contrast, if we find that kids make predominantly "other" errors, it could suggest that they lose interest in the task entirely or do not understand the task and respond randomly.

Results

Memory Check

Responses to individual memory check questions (i.e., *which object were you supposed to watch?*) were averaged over the 10 experimental trials to yield a Memory Accuracy score for each participant. Memory Accuracy data are presented in Figure 2.

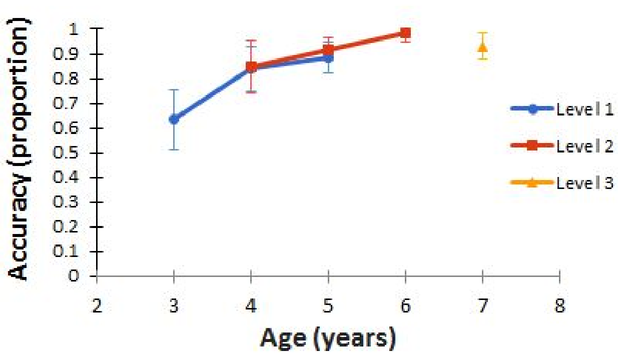

Figure 2. Tracking accuracies for each age and difficulty level, both with and without memory-incorrect trials.

In all conditions and age groups Memory Accuracy was above chance (25% given four response options, all one-sample *t*s>6.2, *p*s<0.0001). To investigate possible effects of age and difficulty, memory accuracy scores were submitted to a 2-way ANOVA with both age as difficulty level as between-subject factors. This analysis indicated a main effect of age (F (2, 128)= 32.2, p<0.0001).[2] There was no effect of difficulty and no age-by-difficulty interaction (both Fs<1.34, ps>0.24). Therefore, any differences in object tracking accuracy between difficulty levels were unlikely to stem from differences in the strength of encoding of the target objects.

Error Analysis

For this analysis, we excluded trials in which the participant failed the memory check, as encoding errors were a separate type of error that we analyzed separately. We compared the rate of each error type to chance, assuming that the participant response was randomly distributed over the incorrect squares of the grid. Chance was estimated by simulating final states of 10,000 TrackIt trials for each level. Chance levels are given in Table 3.

Table 3: Chance probability of each error type assuming the participant response is uniformly distributed over the grid.

Error Type	Level 1	Level 2	Level 3
Correct	0.0625	0.0278	0.0278
Spatial Resolution	0.0434	0.0426	0.0277
DSR	0.3606	0.1514	0.4814
Distractor	0.2131	0.4449	0.1962
Uncategorizable	0.2114	0.1004	0.1084
Other	0.109	0.2329	0.1585

Note: DSR = Distractor Spatial Resolution.

Given that the participant made a tracking error, the average portions of error that were distractor errors was consistently significantly above chance in Level 1 (3-year olds: one-sample t=3.352, p<0.005; 4-year olds: t=4.117, p<0.001; 5-year olds: t=4.756, p<0.0001), Level 2 (4-year olds: t=4.831, p<0.0001; 5-year olds: t=3.805, p<0.001; 6-year olds: t=9.869, p<0.0001), and Level 3 (7-year olds: t=14.065, p<0.0001.

In order to understand how error types change with increasing age, we regressed each error type proportion over age. The β coefficients and F- and p-values for each error type and difficulty level are given in Table 4. In particular, note that only the Distractor, Distractor Spatial Resolution, and Uncategorizable errors in Level 1 show significant decreases with age.

Tracking Accuracy

[2] We omitted difficulty level 3, as only one age group (7 year olds) completed it.

For analyzing tracking accuracy, we included all trials (even those for which the memory check was failed), because we are interested in the true performance of subjects in order to calibrate TrackIt. Furthermore, as shown by a plot of tracking accuracy both including and excluding incorrect memory response trials (see Figure 3), filtering by memory check had little effect on the tracking accuracy scores. For all difficulty levels in all age groups, tracking accuracy was significantly above chance (chance is 1/16 for Level 1 and 1/36 for Levels 2 and 3, *ts*>3.9, *ps*<0.0005).

Table 4: Linear regression results from regressing error type proportions over age

Error Type	β	$F(1,66)$	p
Difficulty Level 1			
Spatial Resolution	-0.0203	1.33	0.253
DSR	-0.0706	6.96	0.010*
Distractor	-0.0653	7.54	0.0078**
Uncategorizable	-0.0444	4.81	0.0318*
Other	-0.0101	0.977	0.327
Difficulty Level 2			
Error Type	β	F(1,65)	p
Spatial Resolution	-0.00915	1.07	0.304
DSR	0.0125	0.185	0.669
Distractor	-0.0229	0.644	0.425
Uncategorizable	-0.0320	1.63	0.206
Other	-0.0142	0.540	0.465

Note: DSR = Distractor Spatial Resolution.
* p<0.05. ** p<0.01

For each of the first two difficulty levels, we saw a significant upward trend effect by an F-test on linear regression (β=0.2302, F=38.33, p<0.0001 for Level 1 and β=0.1427, F=7.605, p<0.01 for Level 2). We could not assess a trend for difficulty Level 3 because we only had one age group for that level.

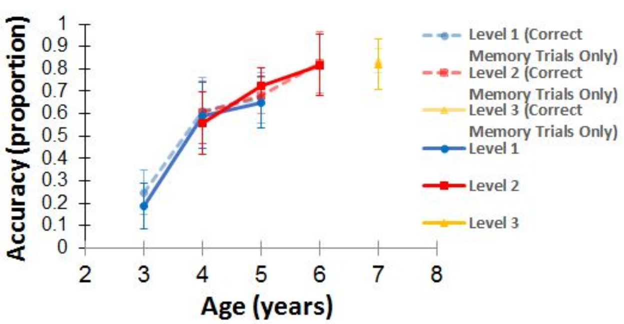

Figure 3. Tracking accuracies for each age and difficulty level, both with and without memory-incorrect trials.

For difficulty Level 1, tracking accuracy of 3-year olds was significantly below that of 4-year olds (two-sample t=-5.05, p<0.0001), but tracking accuracy of 4-year olds was not significantly below that of 5-year olds (two-sample t=-1.02, p=0.315). Similarly, for difficulty Level 2, tracking accuracy of 4-year olds was significantly below that of 5-year olds (two-sample t=-2.18, p<0.033), but tracking accuracy of 5-year olds was not significantly below that of 6-year olds (two-sample t=-0.88, p=0.382).

In the two age groups that performed two difficulty levels (4-5 year olds), two-sample t-tests revealed that performance differences between difficulty levels were not significant (*ts*<1.11, *ps*>0.11).

Discussion

The first purpose of this study was to gain insight into the factors driving improvement by investigating the types of errors made by children. A second purpose was to explore the multidimensional parameter space available within TrackIt, with the goal of identifying both developmental milestones in terms of TrackIt performance as well as appropriate settings for use with children.

Memory Accuracy

Memory accuracy results indicate that encoding error is more prominent in younger children and improves significantly over age. On the other hand, memory accuracy did not differ significantly across difficulty levels, nor was there an age-difficulty interaction effect. Both of these results are encouraging because they suggest that encoding error does not become a confound when using TrackIt with different difficulties across age groups.

Error Analysis

As discussed above, the proportion of distractor errors was consistently significantly above chance in every age group and difficulty. In Level 1 difficulty, distractor, distractor spatial resolution, and uncategorizable errors (all distractor-related errors) significantly decreased over age. Noting that uncategorizable errors indicate a combination of spatial and distractor spatial resolution errors, these together suggest that distractors' effect on performance decreases with increasing age.

On the other hand, the reduction in both spatial and distractor spatial resolution errors may also stem from a reduction in errors due to visuospatial resolution. While this was a known confound when analyzing the improvement in tracking accuracy over age, our analysis enables us to partially isolate these two sources of improvement by showing more specifically that *distractor errors* decrease over time. Since distractor errors are associated only with SSA, and not spatial resolution, this provides a stronger suggestion (as compared to previous results showing only improvement in TrackIt performance) that the improvement in TrackIt performance over age indeed reflects SSA development.

As with previous analyses, we found greatest improvements in performance between 3- and 4-year olds (see Figure 3), which may explain why the significant change in distractor, spatial resolution, and distractor spatial resolution errors was observed only in difficulty Level 1, the only difficulty level at which we tested 3-year olds. We hypothesize that one possible cause of these results, given that changes in the proportion of distractor-related errors occur primarily between ages 3 and 4, is that these ages may be an especially critical period of rapid SSA development.

Tracking Accuracy

In our tracking accuracy results, we observed significant developmental upward trends with age in difficulty Levels 1 and 2, as shown in Figure 3. However, more specific analyses of each difficulty level revealed ceiling effects. These suggest that the parameter combinations for Level 1 and Level 2 may be appropriate settings for assessing 3- and 4-year olds, respectively, insofar as they avoid ceiling effects, but more difficult parameter combinations may be necessary for sensitive measurement with older children.

Since performance of 4- and 5-year olds did not drop significantly from Level 1 to Level 2, a linear increase in number of distractors and grid size with age does not seem to be enough to preserve difficulty across age groups.

Limitations and future directions

Our study did not include 2 year-olds and had limited samples of 6- and 7-year olds. Since significant improvement was observed between 3 and 4 years of age, it may be important to look at 2-year olds also.

The behavioral output of TrackIt is limited in that it records only the participant's response at the end of the trial. In particular, we do not know if participants are *continuously* attentive to the target throughout the trial (on correct trials) or when participants cease to attend to the target (on incorrect trials). Currently, studies are being run in the lab which combine eye-tracking technology with TrackIt and make this information accessible, potentially giving us a more complete picture of how participants behave during the TrackIt task.

Conclusion

The findings of this study lay the foundation for further work using TrackIt to study SSA development over a range of ages by a) identifying parameter combinations appropriate for certain age groups, b) discounting reduction in encoding errors as a confounding source of performance improvement over age, and c) enriching the behavioral output of TrackIt with information about the types of errors children make, and hence the sources of their performance improvements over time. Because of its parametric flexibility, TrackIt can assess SSA across a wide range of ages *in the same basic task*, lowering the risk that changes measured across age are due to different tasks. Additionally, TrackIt has good psychometric properties in general (test-retest reliability, predictive validity, and now a moderate degree of mapping of parametric space). TrackIt thus provides a practical and novel way of measuring attention in an age-range where we know rapid changes occur, but which we haven't had a task to assess with any degree of sensitivity.

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