A Developmental Trend in the Structure of Time-Estimation Performance

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Abstract

The current paper reports analyses of the structure of variability in a time-estimation task. Children between 5 and 11 years pressed a button each time they judged that a brief time interval had passed. In two conditions, children either picked their own time interval, their preferred pace, or they were given an imposed pace of 400 ms (2.5 Hz). The resulting trial series were subjected to detrended fluctuation analysis to estimate the complexity of the temporal coordination between child and task. Results show a developmental trend, from an overly random to more clearly fractal performance when the target time interval was predetermined by the experimenter, but not when the target time interval was chosen spontaneously.

Keywords: pink noise; cognitive development; time estimation

Introduction

Central to cognitive development is the question of how to best characterize the progression from a young mind to a more mature one. Does the trajectory include a progression from undifferentiated to differentiated thought, from implicit to explicit thought, from local to global thought, from isolated to interrelated thought, or from concrete to abstract thought? Or is it the other way around? While such developmental proposals differ in a variety of ways, they have one thing in common: They focus exclusively on changes in mental entities, thus baring an important limitation: In discounting the intricate coordination between mind and task environment, these accounts cannot address how such coordination might develop.

The current research uses the development of motor coordination as a model to understand the development of cognitive performance (cf., Riley, Shockley, & Van Orden, in press). Our assumption is that developmental differences in task performance require a coordination of mind and body with the task demands of the environment. In particular, we assume that mind and body conjoin in *interaction-dominant dynamics*, such that changes on any one timescale of mind or body are reflected across all the timescales of the mind and the body (within available constraints). Interaction-dominant dynamics allows the coordination of mind and body with task demands to be perpetually updated, and thus to reside in a state of preparedness, poised to anticipate the available possibilities for behavior within the task environment (Kloos & Van Orden, 2010; Van Orden, 2010; Van Orden, Kloos, &

Wallot, in press). The question addressed in this paper then pertains to the development of such coordination.

Coordination and the Structure of Variation in Repeated Measures

Before a behavior can take place, the mind and body must be coordinated to meet the immediate demands of a task performance. Some of the parts that must be coordinated are changing on fast timescales (e.g., metabolic cell activity), while others are changing on slower timescales (e.g., the movement of the limbs), and still others change even more slowly (e.g., the overt intention to perform as instructed). For adaptive and flexible performance to be possible, all changes must be coordinated to remain consistent, one with another, within limits, and no single timescale should dominate coordination. Thus, in the ideal, a participant maintains a balance among tendencies toward uncoordinated changes, versus tendencies toward overly coordinated changes, in a flexible coupling across the mind and body.

Idealized interaction-dominant dynamics predicts long-range correlations in repeatedly measured response-time data. Such long-range correlations can be visualized as fractal patterns known as pink noise (Van Orden, Holden, & Turvey, 2003). Pink noise has been demonstrated in the variability of reaction time for a wide array of motor and cognitive tasks, including repeated aiming, walking, tapping to the beat of a metronome, time estimation, reading, searching for a target, or categorizing letter strings (Aks, Zelinsky, & Sprott, 2002; Diniz, Wijnants, et al., 2010; Chen, Ding, & Kelso, 2003; Ding, Chen, & Kelso, 2002; Gilden, 2001; Hausdorff, Zemany, Peng, & Goldberger, 1999; Kello, Beltz, Holden, & Van Orden, 2007; Kello, Brown, et al., 2010; Wijnants, Bosman, Hasselman, Cox, & Van Orden, 2009).

Idealized pink-noise dynamics can be contrasted with dynamical patterns in variation that are either uncoordinated and overly random dynamics or overly regular and rigid dynamics. In particular, if coordination is not sufficiently constrained, performance variation will tend towards overly random white-noise fluctuations. In this case, the coordination takes place among overly independent components. If, on the other hand, coordination becomes too constrained, performance variation will tend toward overly regular brown-noise fluctuations. This is consistent with a coordination dominated by components that have slow high-amplitude changes. Both cases may depart from pink noise, a signature of the loss of complexity when the tendencies depart too far from a balance in behavior (Van Orden, et al., in press).

Development of Coordination in Performance

As discussed above, changes in the patterns observed in variability, across a repeatedly measured performance, signify changes in the capacity for coordination among mind, body and task demands. Changes toward less random, coordination, or vice versa towards more regular coordination, can tell us about changes in the respective balance among tendencies.

How then do changes in coordination present themselves in development? A first hint comes from a study of adults in a speeded precision aiming task, the Fitts task (Wijnants et al., 2009). Over five blocks of practice, participants held a stylus with their non-dominant hand and moved it back and forth, touching one of two target dots, at each extreme. As movement times got faster, while sustaining accurate touching of the target dots, the movement times across trials became more long-range correlated. Most important, the variation across movement times changed from overly random, whiter noise converging on the fractal pattern of pink noise. Practice yielded a more constrained yet flexible dynamic in the coordination.

A second hint comes from a developmental study of stride-to-stride variability human gait (Hausdorff et al., 1999). Children between 3 and 14 years of age walked on a treadmill while stride intervals were measured using force-sensitive switches in participants' shoes. Unlike the novice participation in the precision-aiming task, the less practiced performance of the youngest children spanned a range extending from overly regular brown-noise variation to pink noise. With increasing age, however, the variation in stride intervals converged within a narrower range near pink noise. In other words, while the final performance in both the adults' precision-aiming task and stride intervals of children, trended toward pink noise, the convergence came from opposite directions, whiter noise in the training task and browner noise in stride intervals — white to pink versus brown to pink, respectively.

The current project took these findings as starting points to investigate coordination in the model task of time estimation. Time estimation has sometimes been seen as a combination of cognitive and motor activity that could be divided cleanly (e.g., Gilden, 1997; Wing & Kristofferson, 1973). More recently, however, time-estimation data with adults was shown to reflect interaction-dominant dynamics. We therefore use this task as a model to investigate the development of mind-body-task coordination in children. Children from 5 to 11 years of age estimated a short time interval repeatedly. In the *preferred-pace* condition, children pressed a button, repeatedly, at a pace that they chose to be comfortable for them. In the *imposed-pace* condition, children estimated repeatedly an imposed target interval of 400 ms. We expected to see a cross-section of changes in the development of coordination, especially in the imposed pace condition. The preferred pace condition allows idiosyncratic compensation that may, or may not, appear in a cross-section of development.

Method

Participants

Participants (33 girls and 37 boys, total) were 5-year-olds (N =12; mean age = 70 months), 7-year-olds (N = 20; mean age 89.7 months), 9-year-olds (N = 18; mean age = 113.1

months) and 11-year-olds (N = 20; mean age = 136.2 months). They were recruited from daycare centers and elementary schools in the greater Cincinnati area to participate in either the preferred-pace condition or the imposed-pace condition (N = 35 per condition).

Apparatus

The button used to record a child's time estimates was a force sensor (Biometrics Ltd., Ladysmith, VA), attached to the top of a round Macintosh computer mouse. The mouse was small enough to fit easily into a child's hand. Data were collected and recorded on a PC computer using *DataLINK PC Software* v. 3.00 (Biometrics Ltd., Ladysmith, VA).

Procedure

Participants were tested individually, either in the lab or at their school. The cover story involved a robot that needed power to return to its planet (see Figure 1). He can get power through a power pod (the force sensor), provided the power pod is pressed at the exact rate of the robot's energy pulse. For the duration of the task, a power-point display was used with a grid of 30 stars, arranged in five rows of six. Each star contained the prompt 'Give Me Power'. Children were told that the give-me-power stars would turn into robot food, as they repeatedly pressed the button. The robot could return to his planet once all of the stars are replaced by robot food.

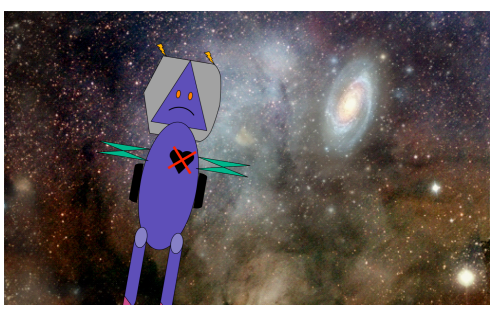

Figure 1: Example of the introduction slide, depicting the robot with 'no energy'.

Children participated in one of two conditions. In the preferred-pace condition, children were told that the robot would get power if the button was pressed at a constant pace that suited the child. The robot would get no power were the button to be pressed too fast, or pressed too slowly. To set the pace, children pressed the button in about 30 time estimates, in which they found their preferred pace. Once the child had found a rhythm, the researcher reminded the child how important it was to keep pressing that way until the end of the game, after which data collection began.

In the imposed-pace condition, a metronome was sounded during the initial phase, set to 400 ms (2.5 Hz). The researcher explained that the metronome pace is the energy pulse of the robot and asked the child to press the button at the same pace as the energy pulse. After about 30 button presses, with the metronome turned on, the metronome was switched off, and the child was asked to "remember in their head" when to press the button, and to continue pressing the button, at the same pace, until the end of the game. Data collection started when the metronome was switched off.

With the start of data collection, a PowerPoint display was initiated, which continued for 10 minutes, to provide participants with a sense of their progress through the experimental session. The PowerPoint appeared on a computer screen, displaying a horizontal bar near the bottom of the screen, which filled in from left to right, taking 20 seconds to accumulate continuously. The fill-in rate was independent of the participant's button presses to avoid feedback about the child's time estimates.

Each time the bar filled to its right-most point, a 'Give-Me-Power' star changed to become a circle that bore the word 'Power.' A star at the top left of the screen changed first, followed next by its adjacent star to the participant's right, and so on, left-to-right and top-to-bottom. Once the first row of stars had all changed to 'Power,' a 'Level 1' sign appeared, followed by "Level Up!" When the second row of stars had all changed to 'Power,' a 'Level 2' sign appeared, again followed by "Level Up!", and so on, through Level 4. After the fourth row was complete, a 'Level 4' sign appeared, followed by "Expert Level". At the end of the session, when the last row of stars had all changed to 'Power,' the robot appeared, smiled, and then flew off to its planet.

Results

Trial series consisted of pressing the button, releasing the button, pressing the button again, releasing the button again, and so on. The time between two button presses (and two button releases) is composed of two events: the time between releasing the button and pressing it again (referred to as 'button press time') and the duration that the button remains in contact before being released (referred to as 'button contact duration') For both of these measures, the analyses required several hundred data points and participants ranged from 400-1500 data points. Fewer data points yield less stable estimates of the δ statistic.

Kello, Anderson, Holden and Van Orden (2008) had found previously that button press times can vary independently of button contact durations and their patterns of variation can be manipulated independently (see also Holden, Choi, Amazeen and Van Orden, in press). Thus, the response-component of removing the finger from the button (button contact duration) appears to reflect different task constraints than the response component of pressing the button (button pressing time).

Developmental differences in time estimation may be more closely associated with the act of pressing the response button than releasing the button, or so we anticipated from previous findings. Consequently, for the analyses, we created a button contact-duration data-series and a button press-time data-series, for each child, and subjected these data to detrended fluctuation analysis (a measure of the pattern of the structure of the variation across a data series). The resulting statistic, δ reveals the scaling relation between

magnitude of change and frequency of changes at particular magnitudes (Peng, Havlin, Stanley, & Goldberger, 1995). The statistic δ in the presence of random white noise would be approximately δ = 0.5, for pink noise it would be approximately δ = 1.0, and for brown noise it would be approximately δ = 1.5. The δ statistic can be transformed into a fractal dimension (FD); A FD = 1.5 indicates white noise, and a FD = 1.2 indicates pink noise. We are most interested, as described, in the direction of change in the noise structure across the cross-section of development.

Figure 2 shows the mean δ for button contact durations, as a function of age and condition. Consistent with previous findings, there was no reliable change in δ for button contact durations, due to condition, and this null result extended as well to age (and there was no reliable age x condition interaction, Fs < 1). Indeed, the correlation between age and δ was low for both of the pace conditions (preferred pace: r = .004, imposed pace: r = .20). Also consistent with previous findings, mean δ (M = 0.74) was relatively closer to the δ = 1.0 of pink-noise, than to white noise (cf. Kello et al., 2008; Holden et al., in press).

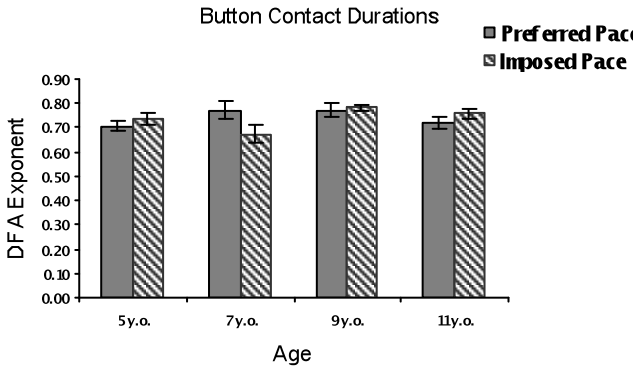

Figure 2: Mean DFA for button contact durations.

How did coordination differ between releasing the button (button contact duration) and pressing it once again (button press time)? Figure 3 portrays the mean δ statistic across these data series as a function of age and condition. Planned contrasts revealed that age did not reliably affect the δ statistic in the preferred-pace condition, r(33) =.17, p > .05), but produced a reliable developmental trend in the imposed-pace condition, r(33) = .45 p <.01), this despite the imbalance of numbers of participants, with fewer children represented at age 5. Older children exhibited less random 'pinker' variation in data series compared to younger children in the imposed-pace condition.

Discussion

Developmental questions that focus exclusively on hypothetical changes in mental entities, share a common limitation: they do not show substantive interest in the interaction and coordination of mind and body to keep pace with changing demands in a task environment. Further, they cannot address how such coordination might develop. This becomes particularly salient in a contrast with respect to general systems theory or complexity theory, where the first question one must ask, to decide methods and analyses, is "How do the system's components interact?" (Holden et al., 2009).

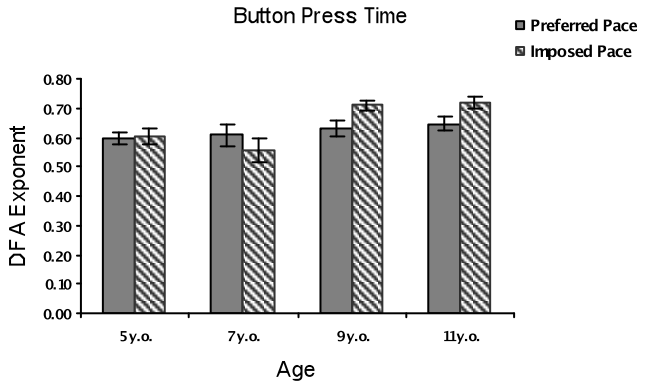

Figure 3: Mean DFA for 'button press time' data series.

The question was posed here, as concerns the development of the coordination among mind, body and task demands. Children of different ages performed time estimations, repeatedly, at their preferred pace or at an imposed target pace of 400 ms (2.5 Hz). Results showed that children across the age-range could perform the task, and all produced variation in performance near the pink noise predicted by interaction-dominant dynamics. The locus of developmental changes was in the time between releasing a response button and pressing it again for the next judgment. Also, the developmental trend that appeared, appeared only in the condition of an imposed pace.

Interestingly, the fractal structure of variation changed in development as a trend from whiter noise for younger children to pinker noise for older children. Thus the development trend in the imposed pace may suggest an increase in the capacity to follow instructions, stay on task, and capitalize on the constraints inherent in an imposed pace of responding. It is even possible that the developmental changes, in the direction of pink noise, coincide with an increase or a refinement in the capacity for voluntary control. The same account, however, could accommodate the same result as a change in involuntary control that decreases tendencies toward random variation. The more basic idea that is entailed is the tradeoff among the tendencies toward random or overly regular dynamics in the coordination of the mind and body with task demands (Kloos & Van Orden, 2010; Van Orden, 2010).

Our results describe how development of time estimation performance proceeds from younger to older children: Stronger long-range correlations that indicate more strongly coupled component interactions, giving rise to a more pronounced fractal pattern in the observed performance.

That is, the organization of body and mind becomes more closely intertwined, yielding a more regular coordination through development compared to the more random variation in the performance of younger children.

Perhaps, the embodiment of component dynamics in younger children is not yet sufficiently coupled, voluntarily, to sustain reliable adjustments to the changing task demands, across the repeatedly measured time estimates, at the imposed pace of the target, distinguishing one judgment from the next. This issue is less salient when the child responds at their preferred pace, which may better reflect or compensate for their developmental status, at every age of development.

It is known, for example, that the optimal pace for time estimation, at an imposed pace, changes throughout the lifespan (McAuley, Jones, et al., 2006). In this light, the demands of keeping a fixed imposed pace supplies unsystematic perturbations of time estimates, reflecting the distance from preferred pace, and whiten the variation in performance. The latter hypothesis would also suit changes due to practice, from Wijnant et al., (2009). The change to pinker noise, in that case, could be due to compensation for the deviations from preferred pace, which would have remained constant, presumably, throughout the blocks of practice. Again these two kinds of hypotheses are not distinguished in the present data, and will be pursued soon in our future research. The sole hypothesis that is distinguished clearly in these data is the tradeoff among tendencies toward random variation with tendencies toward regular variation, and its prediction of the developmental trend that we have observed.

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