Croatian Journal of Education
Vol.26; No.1, pages: 163-184
Original research paper
Paper submitted: 12th April 2023
Paper accepted: 15th May 2023
https://doi.org/10.15516/cje.v26i1.5318

Repetitive Movement Timing of Preschool Children and Young Adults Assessed by the Wing-Kristofferson Model

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Abstract

Synchronization of movement with the external pacing stimuli by use of finger tapping is a widely used paradigm for assessing the accuracy of timekeeping and repetitive motor timing. In the current study, developmental differences in repetitive movement timing between preschool children and young adults were assessed. The study showed that the length of the interresponse intervals (IRI) of children was significantly shorter than IRI's of adults, and significantly more variable. The use of Wing-Kristofferson model allowed the separation of overall variability into motor and clock components. In both groups clock-related variability was larger than the motor-related one, and again, children variance components were both significantly higher than those of young adults. The observed differences in timing accuracy, detected at the central level, were explained in light of the development of cognitive processes, especially attention, but they are likely connected to the other motor control factors such as error correction and possible use of feedback.

Key words: *age-related differences, motor timing, sensory-motor synchronisation, tapping, young children, W-K model.*

Introduction

Time processing

Time and space essentially shape human existence and behavior. Just as the brain possesses mechanisms to track and orient the body in space (Yin & Troger, 2011), cognitive and perceptual processing, as well as motor actions, depend on processing time. Production of skilled movements requires adequate temporal information which determines the initiation and termination of the movement i.e. "timing"(Yamazaki & Nagao, 2012).

Human motor behavior is highly temporally organized, and accurate timing is critical for all motor acts. We have to accurately anticipate moving and stopping the car in a traffic jam, we have to make the just-in-time step from the moving elevator in a shopping mall, or coordinate the swing of the racket with the movement of the ball approaching us at high speed. Hence, the ability to translate perceptual and cognitive representations of a temporal scheme into precise action (Green & Williams, 1993) is a substantial part of many common daily activities, but it also defines our proficiency in music, dance, or sport.

Moreover, the computation of time represents a basic aspect of cognition (Matell & Meck, 2004). For example, decision-making has its temporal order and temporal organization is a fundamental feature of episodic memory where serial events compose a unique experience (Tulving, 1983).

WK model of timing

Timing of repetitive movements is often assessed via *synchronization - continuation* paradigm first applied by Stevenson over a century ago (as cited in Collyer & Church, 1998), but later improved and used by many researchers from a variety of approaches and disciplines (i.e., movement sciences, neuroscience, experimental psychology, clinical sciences and other). In that model of movement, the subject is initially introduced to the train of stimuli to which he or she must synchronize by making repetitive tapping movements, mostly with the index finger. After the pacing signal has been terminated, which usually occurs after 20 seconds or so, the subject must continue making periodic movement at a given frequency.

Based on that movement paradigm, Wing and Kristofferson (1973a, 1973b) developed a model of timing *(W-K model)* assuming that movement is initiated by a central timing system *(clock)* while the *motor implementation* system must translate the signals into a movement that imposes delay. The clock and motor processes are shown in Figure 1. At the top level of the panel, the timer is shown *(clock)* which generates a series of pulses (C) equivalent to the duration of the *interstimulus interval* (ISI). Each pulse triggers a motor response (tap), with a variable delay (MD) which separates the trigger and the motor response. The duration of the *interresponse intervals* (IRI), or the time duration between two successive motor responses, is determined by the current and previous motor delay. For example, if the motor implementation contains a delay, the current interval will be lengthened and the following one will be shortened (see the bottom right side of the panel in Figure 1). Consequently, adjacent intervals are negatively correlated, that is to say - motor delay variability yields negative covariance between the consecutive IRIs. Considering that no such dependency was observed in clock variability, longer or shorter intervals of the clock would not affect the following IRIs.

The model proposes independency of the *clock* component (or central timing) and the *motor implementation* component.

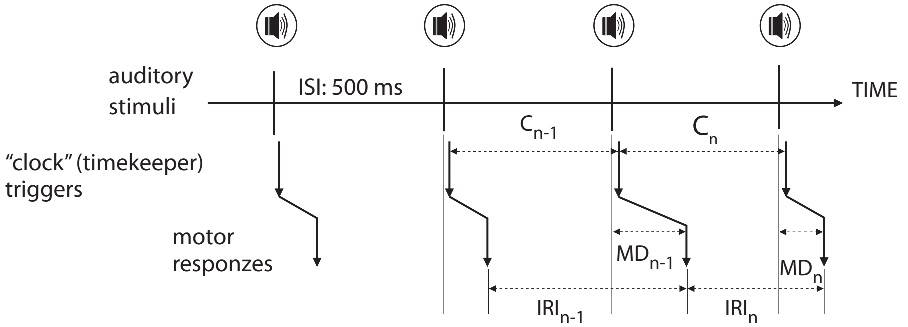

Figure 1. W-K model denotes clock and motor processes. In the processes of a clock (C), a series of pulses is created which reflects the length of the interstimulus interval and induces a tap with motor delay (MD) which is variable and defines the length of interresponse interval (IRI) (Sketch based on Birkett & Talcott, 2012)

Assumptions of independency are based on the idea that the timekeeper determines when the movement should be initiated but does not know how the implementation was accomplished, on the other hand, the motor process does not know whether the clock is accurate or not. Building on this assumption is the the W-K model's most important facet , which is the capability of the model to separate the clock from the motor variance. However, the model's second assumption that the system has to operate without feedback, in an *open-loop* fashion, should also be considered.

The crucial dependent variable in continuation tapping is the *interresponse interval(s)- (IRI)* that is, the duration of the time interval between two successive taps. Considering the theoretical standpoint of independency, Wing and Kristofferson (1973 a,b) assumed that motor and clock processes are represented as random variables with normally distributed variances, which means that a randomly bigger motor delay would cause a lengthening of the current IRI and a shortening of the following one (Figure 1).

The length of any IRI can be depicted from $VAR(IRI) = VAR(C) + 2VAR(MD)$, where $VAR(IRI)$ represents a total variance of the response, while $VAR(C)$ and $VAR(MD)$ are *clock* and *motor variance*, respectively.

According to the W-K model, variances of clock and motor implementation processes can be estimated from the covariance of the IRI. Motor delay variance can be estimated from the *Lag1* autocovariance $AUTOCOV\ (1) = -\ VAR\ (MD)$, considering that the total response variance can be obtained directly from raw data, and the clock variance can then be obtained by algebraic substitutions.

Sensory motor synchronization and its development

Sensory motor synchronization, assessed via the W-K model, has been widely used in diverse clinical samples, i.e. Parkinson's and Huntington's disease (Freeman et al., 1996; Harrington et al., 1998, O'Boyle et al., 1996), cerebellar disorders (Ivry & Keele, 1989; Provasi et al., 2014), ADHD (Birket & Talcott, 2012; Toplak & Tannock, 2005), dyslexia (Wolff et al., 1990; Birkett & Talcott, 2012; Thomson et al., 2006), learning impairment in children (Waber et al., 2000), schizophrenia (Martin et al., 2014), autism

(Karaminis et al., 2016), speech and language impairment (Corriveau & Goswami, 2009) and others.

Studies repeatedly showed differences between clinical and control groups in motor timing tasks, with an increased variability of IRIs in clinical groups, which represents typical findings.

However, Waber et al. (2000) found that IRI variability has predicted achievement in reading, spelling, and maths, not only for learning impaired but also for normally developing children.

Several studies also aimed to depict timing control and sensorimotor synchronization from a developmental perspective in typically developing children and adults. These results seem to imply that *sensitivity to time* develops from an early age (Droit-Vollez, 2016). Even babies can learn the temporal structure and rhythmicity of maternal speech and can respond to small temporal alterations in an anticipated rhythmic sequence (Delavenne et al., 2013; Brannon et al., 2004). Temporal accuracy and the ability to produce complex rhythmic patterns increase across ages 2 to 13 years (Green & Williams, 1993). Bobin-Bègue and Provasi (2008) implied that even very young children from age one onward can synchronize their manual taps with external rhythms if they are near their spontaneous motor tempo. However, during childhood, children increase the range of possible tapping frequencies while the spontaneous motor tempo for children aged 2 – 7 falls between 400 and 500 ms (Bobin-Bègue & Provasi, 2008; Bobin-Bègue et al., 2014; McAuley et al., 2006). An adult level of time sensitivity may be reached at about 8-9 years (Droit-Vollez, 2016) although some age differences may still persist in more complex time judgments.

Developmental differences in time estimation are also related to the temporal task, which is used, *i.e., bisection, generalization, or reproduction*, among which, *temporal reproduction* seems to be the most demanding for children (Droit-Vollez et al., 2015).

Rhythmic tapping is a sort of temporal reproduction task in motor form, and the fact that developmental effects and age differences in normally developing populations in repetitive motor timing are far less researched than the perceptive timing behavior renders the main motivation for the present study. Therefore, the current study has two main goals. Firstly, it aims s to establish possible developmental differences between two subsamples in repetitive movement timing by assessment of IRI's and IRI's variability. Secondly, y the study aims to partition the variance using W-K model and to compare the clock and motor related variance between the groups.

Methodology

The subjects

The subjects were 106 children (57 girls) at the age of 5 (*M*=5.64; *SD*=0.3) and 115 adults (71 females) aged 19-24 (*M*=21.42; *SD*=1.32). Written informed consent was obtained from the parents of the children before the measurement was performed, while the adults personally gave their consent on-site.

The children were recruited from local kindergartens and the adults were university students. The subjects were included if they were not sight or hearing impaired, if they did not have a neurological, muscular, or psychiatric disorder and if they were not trained musicians. The experiment was carried out individually in sound a attenuated room. The adult sample was assessed by the first author while the children were assessed by two kindergarten teachers who were trained by the first author. Handedness in the adult sample was established using the *handedness inventory* (Oldfield, 1971), while the children were observed earlier by their teachers in activities of picking objects from the table and colouring the book.

For their participationin the study the students received course credits while the children were awarded with tatoo stickers and a small portion of ice cream after their lunch. The research was carried out according to the Declaration of Helsinki.

The task and the procedure

Finger tapping was performed using flexion and extension of the index finger of the dominant hand. The responses were collected on a wired mechanical keyboard (Corsair K65) connected to the desk computer which was equipped with dedicated software. The latency of the keyboard was 0.1 ms and maximal polling rate (refreshing rate) was 8000 Hz. The tapping frequency was set to 2 Hz which defined the target interval at 500 ms. The pacing tones at 1000 Hz in the length of 50 ms and at 60 dbSL were presented by the computer.

The subjects were instructed to start tapping with the index finger in synchrony with the pacing tones as soon as they hear the sound and to continue tapping, without the interruption when the sound ceases, until the stop screen is shown. Five trials were performed in a single recording session with a pause between trials. Each trial consisted of 20 paced tones after which the tapping was recorded for 30 seconds or about 60 responses. The first five responses were ignored because of the adaptation (Birkett & Talcott, 2012), and the following 31 responses were analyzed in the W-K model.

An invalid attempt was denoted as the one in which the IRI was less than or larger than 50 % of the target interval (less than 250 ms or larger than 750 ms) based on criteria from several studies (Birkett & Talcott, 2012; Greene & Williams, 1993; Ivry & Keele, 1989). The attempts which fell out of the determined range were deleted, and if subjects had ten or more invalid attempts in the trial, they were removed from the analysis.

Positive Lag 1 autocorrelation during the estimation of variances in the W-K model is not a rare finding in the studies. However, that represents a violation of the model because positive autocorrelation produces negative motor variance and therefore enlarges clock variance (Green & Williams, 1993). In such occurrences, a value of zero was entered as a value of motor delay, and the total IRI was used for clock variability estimation, which is in accordance with established practice (Birkett & Talbot, 2012; Bolbecker et al., 2011; Green & Williams, 1993; Lundy-Ekman et al., 1991).

Results

One child was non-cooperative and failed to complete any of the trials, whereas 19 children had more than ten attempts outside the range of ±50 % of the ISI, and those were removed from all analyses (11 of them were girls). For the latter reason, two adult subjects were also removed from the analysis. The methodology of the W-K model was applied in the second trial. Regarding negative motor delay variances, 21 such cases were found in children and 19 in adults. That amounts to 20 % of all the subjects, which is comparable to other studies (i.e., 24 % in Bolbecker et al., 2011).

Gender differences were not found in either children or adult groups of the subjects in none of the dependent variables.

To test the differences in the duration of IRIs, and the differences in variability of IRIs expressed in SD, two split-plot ANOVAs were performed. In both of them, *trials* were within factor, while the *group* (children – adults) served as a between factor. In the ANOVA for IRI durations (Figure 2), Mauchly's test of sphericity was significant (p=.000), and the epsilon value was greater than .75, therefore Huyn-Feldt adjustment of degrees of freedom was used. The ANOVA was significant for the main effect of *time* ($F(3.23,646.48)=4.23$, $p=.005$, $\eta^2_p=.021$), but not for the interaction *group x time* (p=.74).

Pairwise comparisons revealed that IRI in trial 1 was significantly longer than IRI in trial 4 and IRI in trial 5 (p<.05), whereas IRI in trial 5 was significantly shorter than IRI in trials 2 and 3 (p<.05).

Between-subjects analysis was significant ($F(1,200)=12.24$, $p=.001$, $\eta^2_p=.058$). Post-hoc tests revealed that children's IRIs were shorter than the adults' on average for 30.12 ms (p=.001; mean children = 401.39, SE=6.44; mean adults = 431.52, SE=5.72).

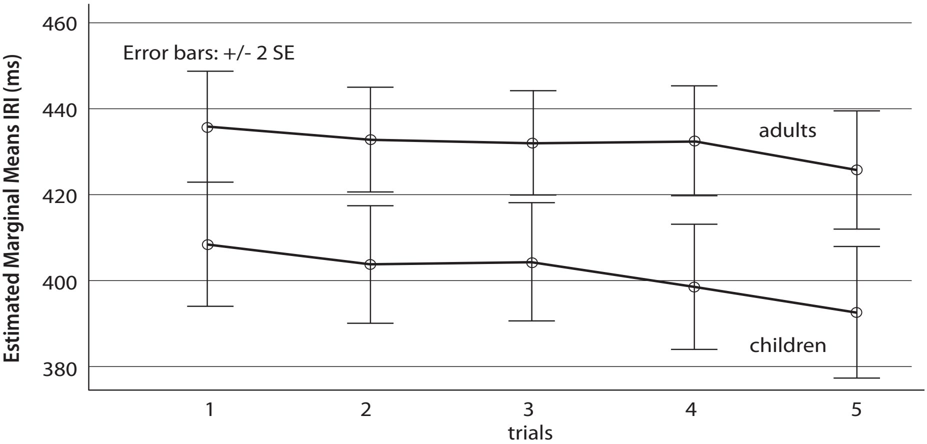

Figure 2. Means and standard errors of interresponse intervals for children and young adults, with the visible presence of drift in time interval series

The second ANOVA *(group x trial)* performed on standard deviations (Figure 3) of IRI's did not detect significance either for interaction (p=.28) or the main effect (p=.55). However, there was a significant between-subjects effect ($F(1, 200)=579.59$, p=.000,

η^2_p = .74). The post hoc test revealed that the timing performance of children was much more variable (*SD* mean = 91.01, *SE*=1.88) than that of adults (*SD* mean = 30.37, *SE*=1.67).

Wing-Kristofferson analysis

In Figure 4, mean values are displayed for the total IRI variability, clock variability, and motor delay variability, as obtained by W-K methodology.

To minimize the influence of *drift* on the variance estimate, which occurs in long series, the regression line was fitted to each individual trial, and then the variance of the deviations was calculated. That represented the total score variance which was then decomposed for each subject into the clock and motor variance. The motor delay variance was estimated by obtaining the Lag 1 covariance while the clock variance was estimated by subtraction the motor from the total variance. As expected, the clock variance surpassed the motor variance in both groups. Significant differences were obtained in all three variance components (p=.000), with mean values pointing to much larger variability in the performance of the children (Figure 4).

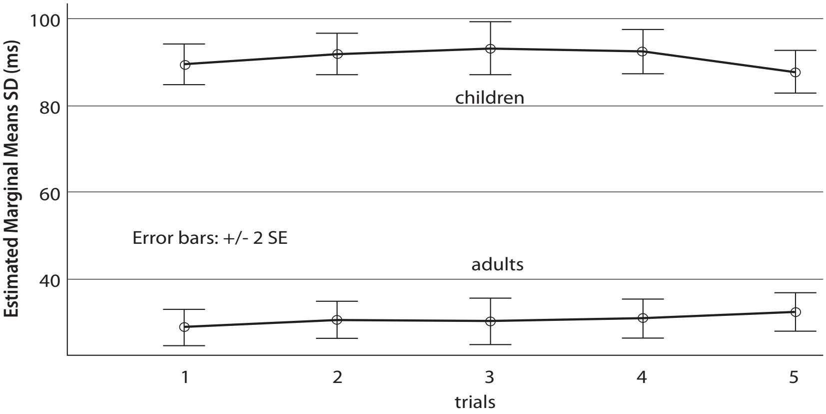

Figure 3. Variability of IRI expressed in SD for children and young adults

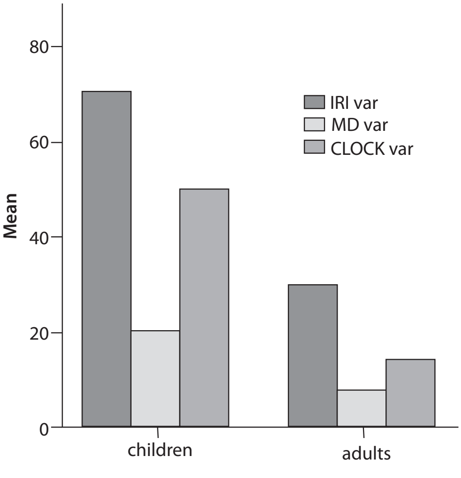

Figure 4. Variances of the total IRI, the motor, and the clock of children and young adults

Discussion

The research attempted to assess repetitive timing ability in children and young adults. As expected, tapping performance was less accurate in children than in adults. Although both groups underestimated the target interval, children on average, tended to tap much faster than the adults, as indicated by the mean IRI which was farther apart from the ISI than the mean IRI of the adults. A boundary (.058) medium effect size (Cohen, 1988) was found for IRI durations, indicating that 6 % of the variance may be attributed to group differences, which was the primary objective of the research. However, large effect size, which accounted for 74 % of the total variation, showed that the group differences in variability (SD) were significantly more substantial.

The Wing-Kristofferson model was used to enable the separation of the sources of the variances in the rhythmic tapping. Common findings in the studies that the aging effects on timing behavior are caused by the clock and not motor variability, were not confirmed entirely here. Decomposition of the timing variance revealed that, first, the variance of the clock component was larger in both groups than the motor variance, and second, the groups of subjects differed in motor variance and not only in clock variance. However, the differences in the clock component were more pronounced than the differences in the motor component.

Hallez et al. (2019) suggest that children tend to overestimate shorter durations and underestimate the longer ones. The authors speculate that the reason for overestimation is the motor responses that took more time to complete, whereas the underestimation may be caused by motor impulsivity. In contrast, other studies have shown that younger children tend to underestimate all durations (Karaminis et al., 2016).

The studies show that accuracy in temporal reproduction was significantly correlated with working memory capacity (Ogden et al., 2014), which may be explained by the fact that reference duration should be held, managed, and finally compared with the produced duration in working memory. Researchers have also recognized that the development of attention is essential for accurate timing (Droit-Volet, 2016; Hallez & Droit-Volet, 2017). Precise estimation and production of the stimulus of a certain duration have been related to sustained attention as was shown in dual-task experiments using the non-temporal interference effect which negatively affected timing (Bååth et al., 2016; Holm et al., 2017). This is in agreement with the *attentional gate model* of timing (Zakay & Block, 1995), which highlights the competition for attentional resources and postulates that as more attention is allocated to non-temporal processing, smaller amount of attentional capacities is left for time processing which leads to the misestimation of time. The link between attention and timing is also evidenced in clinical populations, for example, attention-deficit hyperactivity disorder (ADHD) includes timing deficiencies (Hove et al., 2017; Valera et al., 2010). Moreover, the large body of research on ADHD points to deficits in the prefrontal cortex (PFC) which regulates attention and behavior through extensive connections to sensory and motor areas and the basal ganglia and cerebellum (Arnsten, 2009). The PFC is the brain structure that matures the last, with the full maturation achieved in late adolescence (Arnsten, 2009; Fuster, 2001). Consequently, the development of attention and decision-making (also judging the time) is protracted, which may explain inaccuracy in children's time estimation.

In sum, the responses of the young children are often random, and the representation of time in reference memory is more variable and fuzzier (Droit-Volet, 2016), which, combined with frequent *attentional lapses* (Karampela et al., 2020), contributes to enlarged variability in time estimation.

From the motor control point of view, it is tempting to speculate that variability may partially arise from error correction attempts, and the "cost" of error correction is an increased variability and dependence between inter-response intervals (Voillaume, 1971, as cited in Semjen et al., 2000).

This is in disagreement with Lewis and Miall (2003), who consider timing in the sub-second range "automatic" and not relying on cognitive control, moreover, it is also usually considered that the continuation phase of the W-K model operates in an open-loop mode (automatic mode). However, there is still an ongoing debate (since Schmidt, 1980) about the involvement of feedback processes in motor timing. For example, Madison and Delignières (2009) determined 700-800 ms (and above) as a lower point for the feedback-based error correction. On the other hand, in a study by Peters (1989) on the role of interval duration in conscious perception, a rate of 300 ms emerged as a point when movements are initiated and experienced individually. Perhaps it is, therefore, possible that some of the subjects in the current study perceived the current tapping rate in the continuation phase as non-adequate to the remembered tempo and tried to change the rate, which resulted in a more variable trial.

The results obtained in the current study are in accordance with the observation made by Aschersleben (2002) about a systematic error in tapping, manifested in a way that taps usually precede clicks by several tens of milliseconds, which is also called "negative asynchrony" or "synchronization error". Aschersleben (2002) assumes that synchrony is established at the level of central representations, while the tap is represented by its sensory feedback, therefore, negative asynchrony, according to the author, arises as a consequence of differences in peripheral and/or central processing times.

Conclusion

The Wing and Kristofferson model (1973 a, b) allowed the separation of time-keeping components and evaluation of sources of variability. It was clearly established that the central timekeeper component contributes to the variability of IRI more than the motor component of the task. Children significantly differed from young adults in the overall variability, but also in the decomposed components of variability. As an advantage of this study, it can be indicated that a fairly large sample was used, however, as a limitation and direction for further experiments, it is recommended that assessment of the involvement of other related constructs, such as working memory and/or attentional capacities should be considered.

Acknowledgment and funding

This study was supported by a grant from the University of Zagreb.

The authors thank the management and preschool teachers (I. Kolarić, A. Sudec, M. Sakač, K. Apari, P. Radoš) from the kindergartens located in Ludbreg and Varaždin.

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Tajming repetitivnih pokreta predškolske djece i mladih odraslih osoba procijenjen prema Wing-Kristoffersonovu modelu

Sažetak

Sinkronizacija pokreta s vanjskim ritmičkim podražajima uz uporabu tapinga prstima naširoko je korištena paradigma za procjenu točnosti procjenjivanja vremena i repetitivnoga motoričkog tajminga. U ovom radu procijenjene su razvojne razlike između predškolske djece i mladih odraslih osoba u repetitivnom motoričkom tajmingu. Pokazalo se da je duljina intervala između odgovora (IRI) djece značajno kraća od IRI-a odraslih te da je varijabilnost značajno veća. Uporaba Wing-Kristoffersonova modela (WK) motoričkoga tajminga omogućila je razdvajanje ukupne varijabilnosti na motoričku komponentu i komponentu sata. Varijabilitet povezan sa satom u obje skupine bio je veći od varijabiliteta povezanoga s motoričkom komponentom, a komponente varijance kod djece i ovdje su bile značajno veće nego kod mladih odraslih osoba. Uočene razlike u točnosti procjenjivanja vremenskih intervala, otkrivene na središnjoj razini, objašnjene su u svjetlu razvoja kognitivnih procesa, posebno pažnje, ali su vjerojatno povezane i s čimbenicima motoričke kontrole poput ispravljanja pogrešaka i mogućega korištenja povratne informacije.

Ključne riječi: *dobne razlike, motorički tajming, predškolska djeca, senzorno-motorička sinhronizacija, taping, W-K model.*

Uvod

Procesiranje vremena

Vrijeme i prostor bitno oblikuju ljudsko postojanje i ponašanje. Baš kao što mozak posjeduje mehanizme za praćenje i orijentaciju tijela u prostoru (Yin i Troger, 2011), kognitivno i perceptivno procesiranje, kao i motoričke akcije, ovise o procesiranju vremenskih intervala. Izvedba uvježbanih pokreta zahtijeva odgovarajuće vremenske informacije koje određuju početak i završetak akcije, tj. „tajming" (Yamazaki i Nagao, 2012).

Čovjekove motoričke akcije vremenski su vrlo organizirane, a precizni tajming ključan je za sve motoričke radnje. U svakodnevnom životu potrebno je, npr., točno predvidjeti pokretanje i zaustavljanje automobila u prometnoj gužvi, ili pravovremeno napraviti korak pri silaženju s pokretnih stepenica u trgovačkom centru, ili uskladiti zamah reketa s kretanjem loptice koja se približava velikom brzinom. Stoga je sposobnost prevođenja perceptivne i kognitivne sheme vremenskih intervala u preciznu akciju (Green i Williams, 1993) bitan dio brojnih dnevnih aktivnosti, ali također predodređuje vještinu u glazbi, plesu ili sportu.

Štoviše, komputacije vremenskoga intervala predstavljaju osnovni aspekt kognicije (Matell i Meck, 2004). Na primjer, donošenje odluka ima svoj vremenski slijed, isto kao što je vremenska organizacija temeljna značajka epizodnoga pamćenja pri čemu niz događaja čini jedinstveno iskustvo (Tulving, 1983).

Wing-Kristoffersonov model tajminga

Wing-Kristoffersonov model tajminga repetitivnih pokreta često se procjenjuje putem *sinkronizacijsko-kontinuacijske paradigme* koju je prvi primijenio Stevenson prije više od jednoga stoljeća (prema Collyer i Church, 1998), a koju su paradigmu kasnije poboljšali i koristili mnogi istraživači iz različitih pristupa i disciplina (znanosti o kretanju, neuroznanosti, eksperimentalne psihologije, kliničkih znanosti i dr.). U tom modelu kretanja, subjektu se inicijalno prezentira niz podražaja - signala vođenja (najčešće audio ili vizualnih signala) s kojima se mora uskladiti izvodeći *taping*, uglavnom kažiprstom. Nakon prekida signala, što se obično događa nakon otprilike 20 sekundi, ispitanik mora nastaviti izvoditi *taping* u zadanoj frekvenciji. Na temelju te paradigme pokreta, Wing i Kristofferson (1973 a, b) razvili su model tajminga (Wing-Kristoffersonov model) pretpostavljajući da je kretanje inicirano središnjim sustavom tajminga, tj. centralnim *satom* (metafora hipotetskoga sustava procjenjivanja vremenskoga intervala u mozgu), dok sustav motoričke implementacije mora prevesti signale u pokret što dovodi do odgode, odnosno kašnjenja. *Sat* i motorički procesi prikazani su na Slici 1. Na gornjem dijelu prikaza vidi se hipotetski *tajmer (sat)* koji generira niz impulsa (*C - clock*) ekvivalentnih trajanju intervala između podražaja (*ISI – interstimulus interval*). Svaki impuls pokreće motorički odgovor (*tap* - dodir), s promjenjivim kašnjenjem (MD - *motor delay*) koje odvaja *okidač* od motoričke akcije. Trajanje intervala između dva uzastopna motorička odgovora (*IRI-interresponse intervals*), određeno je trenutačnim i prethodnim motoričkim kašnjenjem. Na primjer, ako motorička implementacija sadrži kašnjenje, trenutačni interval će se produžiti, a sljedeći će se skratiti (donja desna strana Slike 1). Posljedica navedenoga je negativna korelacija susjednih intervala, drugim riječima – motorička varijabilnost dovodi do negativne kovarijance između uzastopnih IRI-a. Uzimajući u obzir da se takva zavisnost ne primjećuje u varijabilnosti *sata*, duži ili kraći intervali *sata* nemaju utjecaja na uzastopne vremenske intervale između dva odgovora.

Slika 1

U modelu se predlaže nezavisnost komponente *sata* (središnje mjerenje vremena) i komponente motoričke implementacije. Pretpostavke o nezavisnosti komponenenata temelje se na ideji da sustav mjerenja vremena određuje kada treba započeti pokret, ali „ne zna“ kakva je bila provedba, s druge pak strane, motorički proces „ne zna“ je li *sat* precizan ili nije. Iz te pretpostavke proizlazi najvažniji aspekt Wing-Kristoffersonova modela, a to je sposobnost modela da odvoji varijabilitet *sata* od motoričkoga varijabiliteta. Međutim, treba uzeti u obzir i drugu pretpostavku modela, a to je da sustav mora raditi bez povratne sprege, u tzv. *otvorenoj petlji*. Ključna zavisna varijabla u kontinuiranom *tapingu* je interval između dva motorička odgovora - (IRI), to jest trajanje vremenskoga intervala između dva uzastopna dodira kažiprstom. S obzirom na teorijsku postavku nezavisnosti, Wing i Kristofferson (1973 a,b) pretpostavili su da se motorički i procesi *sata* mogu podrazumijevati kao slučajne varijable s normalno distribuiranim varijancama, što znači da slučajno veće kašnjenje motoričkoga procesa uzrokuje produljenje trenutačnog IRI-a i skraćivanje sljedećega (Slika 1). Duljina bilo kojeg IRI-a može se predstaviti s: $VAR(IRI) = VAR(C) + 2VAR(MD)$, gdje $VAR(IRI)$ predstavlja ukupnu varijancu odgovora, dok su $VAR(C)$ *i* $VAR(MD)$ varijanca *sata* i motorička varijanca. Prema Wing-Kristoffersonovu modelu, varijanca procesa *sata* te motorička varijanca mogu se procijeniti iz kovarijance IRI-a, a varijanca motoričkoga kašnjenja može se procijeniti iz Lag1 autokovarijance: $AUTOCOV(1) = - VAR(MD)$. Treba uzeti u obzir da se ukupna varijanca odgovora može dobiti izravno iz vrijednosti trajanja intervala, a varijanca *sata* zatim se dobiva algebarskim supstitucijama.

Senzomotorička sinkronizacija i njezin razvoj

Senzomotorička sinkronizacija, procijenjena pomoću Wing-Kristoffersonova modela, naširoko je korištena u različitim kliničkim populacijama, npr. Parkinsonovoj i Huntingtonovoj bolesti (Freeman i sur., 1996; Harrington i sur., 1998; O'Boyle i sur., 1996), cerebelarnim poremećajima (Ivry i Keele, 1989; Provasi i sur., 2014), ADHD-u (Birket i Talcott, 2012; Toplak i Tannock, 2005), disleksiji (Wolff i sur., 1990; Birkett i Talcott, 2012; Thomson i sur., 2006), kod poremećaja učenja kod djece (Waber i sur., 2000), shizofreniji (Martin i sur., 2014), autizmu (Karaminis i sur., 2016), poremećajima govora i jezika (Corriveau i Goswami, 2009) i drugima. U istraživanjima su se više puta pokazale razlike između kliničkih i kontrolnih skupina u zadatcima motoričkoga tajminga, s povećanom IRI varijabilnošću u kliničkim skupinama, što zapravo predstavlja tipični nalaz.

Međutim, Waber i sur. (2000) otkrili su da varijabilnost IRI-a predviđa postignuća u čitanju, pravopisu i matematici ne samo za djecu s poteškoćama u učenju, već i za djecu urednoga razvoja.

U nekoliko istraživanja ispitivala se kontrola tajminga i senzomotoričke sinkronizacije iz razvojne perspektive, i to kod djece i odraslih koji se normalno razvijaju. Rezultati impliciraju da se osjetljivost u procjenjivanju vremenskoga intervala razvija već od rane dobi (Droit-Vollez, 2016). Nadalje, kako izgleda, čak i vrlo mala djeca mogu naučiti vremensku strukturu i ritmičnost majčinoga govora i mogu reagirati na male vremenske promjene u predviđenom ritmičkom nizu (Delavenne i sur., 2013; Brannon i sur., 2004). Vremenska točnost i sposobnost stvaranja složenih ritmičkih obrazaca povećavaju se u dobi od druge do trinaeste godine (Green i Williams, 1993). Bobin-Bègue i Provasi (2008) impliciraju da čak i vrlo mala djeca u dobi od jedne godine i nadalje, mogu sinkronizirati *taping* rukom s vanjskim ritmovima ako su ti ritmovi blizu njihova spontanoga motoričkog tempa. Tijekom djetinjstva djeca povećavaju raspon mogućih frekvencija *tapinga* dok se spontani motorički tempo za djecu u dobi od 2 do 7 godina smanjuje između 400 i 500 ms (Bobin-Bègue i Provasi, 2008; Bobin-Bègue i sur., 2014; McAuley i sur., 2006). Razina osjetljivosti na vremenske intervale odraslih može se doseći s otprilike 8-9 godina (Droit-Vollez, 2016), iako se neke dobne razlike i dalje mogu pronaći u složenijim prosudbama vremenskih intervala.

Razvojne razlike u procjeni vremenskih intervala također su povezane s temporalnim zadatkom koji se koristi u istraživanju, tzv. *bisekcija*, *generalizacija* ili *reprodukcija*, među kojima se čini da je temporalna reprodukcija najzahtjevnija za djecu (Droit-Vollez i sur., 2015).

Ritmički *taping* je forma reprodukcije vremenskih intervala u motoričkom obliku, a činjenica da su utjecaj razvoja i dobne razlike u repetitivnom motoričkom tajmingu u populacijama urednoga razvoja daleko manje istraženi od perceptivnoga tajminga, predstavlja glavni izvor motivacije za ovo istraživanje. S obzirom na navedeno, istraživanje ima dva cilja. Prvi je cilj odrediti moguće dobne razlike u repetitivnom tajmingu i to u trajanju IRI-a i u varijabilnosti IRI-a, i drugo, u istraživanju se temeljem Wing-Kristoffersonova modela želi particionirati varijanca kako bi se između skupina usporedile *motorička* i varijanca *sata*.

Metodologija

Ispitanici

Uzorak ispitanika činilo je 106 djece (57 djevojčica) u dobi od 5 godina ($M = 5.64$; $SD = 0.3$) i 115 odraslih (71 žena) u dobi od 19 do 24 godine ($M = 21.42$; $SD = 1.32$. Prije mjerenja roditelji djece koja su sudjelovala u istraživanju bili su pismeno informirani o istraživanju i dali su svoj pristanak, dok su odrasli osobno potpisali pristanak prije samoga mjerenja.

Djeca su bila polaznici okolnih vrtića, a odrasli ispitanici bili su iz populacije studenata. Ispitanici su uključivani u istraživanje ako nisu imali oštećenje vida ili sluha, ako nisu imali neurološki, mišićni ili psihijatrijski poremećaj te ako nisu bili školovani glazbenici. Istraživanje je provedeno prema načelima Helsinške deklaracije. Mjerenja su provođena individualno u zvučno izoliranoj prostoriji. Odrasle ispitanike testirao je prvi autor rada, a djecu dvije odgojiteljice koje je uvježbao prvi autor. Dominantna ruka određena je za odrasle uporabom upitnika (*Edinburgh handedness inventory;* Oldfield, 1971), a kod djece ranijom opservacijom odgojiteljica u aktivnostima koje su zahtijevale uzimanje objekata sa stola ili bojanje slikovnice.

Studenti su za svoje sudjelovanje u istraživanju dobili kompenzacijske bodove u nastavnom kolegiju, a djeca su neposredno po završenom testiranju dobila *tatoo* naljepnicu i tijekom ručka malu porciju sladoleda.

Zadatak i procedura mjerenja

Taping prstima izveden je pokretima fleksije i ekstenzije kažiprsta dominantne ruke. Odgovori su prikupljeni na računalnoj žičanoj mehaničkoj tipkovnici *(Corsair K65)* spojenoj na stolno računalo opremljeno namjenskim softverom. Latencija tipkovnice iznosila je 0.1 ms, a maksimalna brzina osvježavanja 8000 Hz. Frekvencija *tapinga* bila je postavljena na 2 Hz što je definiralo ciljni interval od 500 ms. Zvučni podražaji (tonovi u stilu metronoma - 1000 Hz, dužine 50 ms i 60 dbSL) generirani su računalno.

Ispitanici su instruirani da počnu izvoditi *taping* kažiprstom usklađeno sa zvucima generiranim iz računala i to čim čuju zvuk te da ne prekidaju izvođenje kada zvuk prestane, nego da nastave tako dugo dok se na zaslonu ne prikaže natpis za kraj. U jednoj seansi mjerenja izvedeno je pet nizova pokušaja s pauzama između nizova. Svaki niz pokušaja sastojao se od 20 tonova vođenja nakon kojih je sniman nastavak *taping* izvedbe u trajanju od daljnjih 30 sekundi, temeljem čega je zabilježeno oko 60 motoričkih odgovora. Prvih pet odgovora zanemareno je zbog prilagodbe ispitanika (Birkett i Talcott, 2012), a sljedećih 31 odgovor analiziran je u Wing-Kristoffersonovu modelu.

Pokušaji u kojima je IRI bio manji ili veći od 50 % ciljanoga intervala (manje od 250 ms ili više od 750 ms) smatrali su se nevažećim na temelju kriterija iz nekoliko istraživanja (Birkett i Talcott, 2012; Greene i Williams, 1993; Ivry i Keele, 1989). Pokušaji izvan utvrđenoga raspona su brisani, a rezultati ispitanika s deset ili više nevažećih pokušaja u nizu, uklanjali su se iz analize.

Pozitivna autokorelacija (*Lag 1*) tijekom procjene varijanci u Wing-Kristoffersonovu modelu nije rijedak nalaz u istraživanjima. Međutim, takav rezultat predstavlja kršenje postavki modela jer pozitivna autokorelacija proizvodi negativnu motoričku varijancu i stoga povećava varijancu *sata* (Green i Williams, 1993). U takvim se situacijama kao vrijednost motoričkoga kašnjenja (MD) upisivala nula, a kao vrijednost varijabilnosti *sata* upisivana je vrijednost ukupnoga IRI-a, što je u skladu s već ustaljenom praksom (Birkett i Talbot, 2012; Bolbecker i sur., 2011; Green i Williams, 1993; Lundy-Ekman i sur., 1991).

Rezultati

Tijekom mjerenja jedno dijete nije surađivalo te nije uspjelo završiti ni jedan niz, dok je 19 djece imalo više od deset pokušaja izvan raspona od ±50 % ISI, te su njihovi rezultati uklonjeni iz svih analiza (11 djevojčica). Iz potonjega razloga, rezultati dva odrasla ispitanika također su uklonjeni iz analize. Metodologija Wing-Kristoffersonova modela primijenjena je na podatke iz drugog niza pokušaja. Što se tiče negativnih varijanci motoričkoga kašnjenja, 21 takav slučaj pronađen je u djece i 19 u odraslih. To iznosi 20 % od ukupnoga broja ispitanika, što je usporedivo s drugim istraživanjima (npr. 24 % u Bolbecker i sur., 2011).

Razlike prema spolu nisu pronađene ni u skupini djece ni kod odraslih ispitanika ni u jednoj zavisnoj varijabli.

Kako bi se testirale razlike u trajanju IRI-a i razlike u varijabilnosti IRI-a izraženoj u SD, provedene su dvije *split-plot* ANOVE. U obje ANOVE *nizovi pokušaja* predstavljali su *unutargrupni* faktor, dok je *skupina* (djeca – odrasli) služila kao faktor *između* ispitanika. U ANOVI kojom su ispitivane razlike u trajanju IRI-a (Slika 2), ustanovljen je značajan ($p = .000$) Mauchlyjev test sferičnosti, a vrijednost epsilon koeficijenta bila je veća od .75, stoga je korištena Huyn-Feldtova prilagodba stupnjeva slobode. Pokazalo se da je ANOVA bila značajna za glavni efekt vremena ($F(3.23, 646.48) = 4.23, p = 005, \eta^2p = .021$), ali ne i za interakciju *skupina x vrijeme* ($p = .74$).

Parne usporedbe pokazale su da je IRI u prvom nizu pokušaja bio značajno duži od IRI-a u četvrtom i petom nizu ($p < .05$), dok je istovremeno IRI u petom nizu bio značajno kraći od IRI-a u nizovima 2 i 3 ($p < .05$).

Analiza je pokazala i statistički značajne razlike između skupina ispitanika ($F(1,200) = 12.24, p = .001, \eta^2p = .058$). *Post-hoc* testovi otkrili su da su IRI kod djece bili kraći od odraslih u prosjeku za 30.12 ms ($p = .001$; prosječna vrijednost za djecu iznosila je 401.39, $SE = 6.44$; a prosječna vrijednost za odrasle = 431.52, $SE = 5.72$).

Slika 2

Druga ANOVA *(skupine x niz pokušaja)* provedena na standardnim odstupanjima (*SD*; Slika 3) IRI-a nije pokazala značajnu interakciju ($p = .28$) ni statistički značajan glavni efekt ($p = .55$). Međutim, pronađen je značajan efekt *između ispitanika* ($F(1, 200) = 579.59, p = 0.000, \eta^2p = 0.74$). *Post-hoc* testom otkriveno je da su procjene vremenskoga intervala kod djece mnogo varijabilnije (srednja vrijednost $SD = 91.01$, $SE = 1.88$) nego kod odraslih (srednja vrijednost $SD = 30.37$, $SE = 1.67$).

Analiza prema Wing-Kristoffersonovu modelu

Na Slici 4 prikazane su srednje vrijednosti za ukupnu varijabilnost IRI-a, varijabilnost *sata* i varijabilnost motoričke komponente dobivene Wing-Kristoffersonovom metodologijom.

Kako bi se smanjio utjecaj *ubrzavanja (drift)* na procjenu varijance koji se javlja u dugim serijama, u svakom pojedinačnom nizu pokušaja postavljena je regresijska linija, a zatim je izračunata varijanca odstupanja. Navedena je varijanca predstavljala ukupnu varijancu rezultata, koja je zatim za svakog ispitanika raščlanjena na varijancu *sata* i motoričku varijancu. Varijanca motoričkoga kašnjenja procijenjena je pomoću kovarijance (*lag 1*), dok je varijanca *sata* procijenjena oduzimanjem motoričke od ukupne varijance. Kao što se očekivalo, varijanca *sata* premašila je motoričku varijancu u obje skupine. Nadalje, dobivene su značajne razlike između skupina u sve tri komponente varijance ($p =.000$), pri čemu srednje vrijednosti upućuju na puno veću varijabilnost u izvedbama djece (Slika 4).

Slika 3

Slika 4

Rasprava

U istraživanju je procijenjena sposobnost repetitivnoga tajminga kod djece i mladih odraslih osoba. Prema očekivanjima, djeca su pokazala manje precizne izvedbe nego odrasli. Iako su obje skupine podcijenile ciljni interval, izvedbe djece u prosjeku su bile puno brže nego kod odraslih, na što upućuju prosječne vrijednosti intervala između odgovora (IRI), koje su bile udaljenije od ciljnoga intervala (ISI) nego prosječne vrijednosti IRI-a odraslih.

S obzirom na primarni cilj istraživanja, granična (.058) srednja vrijednost efekta (Cohen, 1988) dobivena je za trajanja intervala između podražaja, što objašnjava 6 % od ukupne varijance.

S druge strane, veliki efekt, koji uključuje 74 % ukupne varijance, pokazao je da su razlike između skupina u varijabilnosti (SD) puno naglašenije.

Wing-Kristoffersonov model iskorišten je kako bi se omogućilo razdvajanje izvora varijanci u ritmičkom *tapingu*. Uobičajeni nalazi u istraživanjima, prema kojima su posljedice starenja na tajming uzrokovane varijabilnošću *sata*, a ne motoričkom varijabilnošću, ovdje nisu u potpunosti potvrđeni. Dekompozicijom varijance tajminga otkriveno je, prvo, kako je varijanca komponente *sata* veća u obje skupine od motoričke varijance, i drugo, skupine ispitanika razlikuju se i u motoričkoj varijanci, a ne samo u varijanci *sata*. Ipak, razlike u komponenti *sata* bile su izraženije od razlika u motoričkoj komponenti.

Hallez i sur. (2019) sugeriraju da su djeca sklona precijenjivanju trajanja kraćih intervala i podcijenjivanju duljih. Autori spekuliraju da je razlog precjenjivanja motorički odgovor za koji djeci treba više vremena da bi se izvršio, dok podcjenjivanje može biti uzrokovano motoričkom impulzivnošću. Nasuprot tome, druga su istraživanja pokazala da su mlađa djeca sklona podcjenjivanju svih trajanja, i kraćih i dužih (Karaminis i sur., 2016).

Istraživanja pokazuju kako je točnost u vremenskoj reprodukciji u značajnoj korelaciji s kapacitetom radnoga pamćenja (Ogden i sur., 2014), što se može objasniti činjenicom da referentno trajanje treba održavati u radnom pamćenju, kontrolirati ga, te na kraju i usporediti s proizvedenim trajanjem intervala. Istraživači su također prepoznali da je razvoj pozornosti ključan za precizni tajming (Droit-Vollez, 2016; Hallez i Droit-Volet, 2017). Precizna procjena i proizvodnja podražaja određenoga trajanja povezani su s održavanjem pozornosti kao što je pokazano u eksperimentima s dvojnim zadatcima u kojima je korišten efekt interferencije koji je negativno utjecao na tajming (Bååth i sur., 2016; Holm i sur., 2017). To je u skladu s *tajming modelom usmjeravanja pozornosti* (Zakay i Block, 1995), koji naglašava natjecanje za resurse pozornosti i postulira da - što se više pozornosti pridaje ne-vremenskom procesiranju, manji kapacitet pozornosti ostaje za obradu vremenskoga intervala što dovodi do pogrešne procjene. Veza između pozornosti i tajminga također je dokazana u kliničkim populacijama, na primjer, poremećaj pozornsti i hiperaktivnosti (ADHD) uključuje nedostatke u procesiranju vremena (Hove i sur., 2017; Valera i sur., 2010). Štoviše, veliki broj istraživanja o ADHD-u ukazuje na nedostatke u prefrontalnom korteksu (PFC) koji regulira pozornost i ponašanje i to pomoću opsežnih veza sa senzornim i motoričkim područjima te bazalnim ganglijama i malim mozgom (Arnsten, 2009). PFC je struktura mozga koja sazrijeva posljednja, a to se postiže tek u kasnoj adolescenciji (Arnsten, 2009; Fuster, 2001). Kao posljedica toga, razvoj pozornosti i donošenja odluka (također i procjene vremenskoga intervala) je produljen, što može objasniti netočnost u procjeni vremena kod djece.

Ukratko, odgovori male djece često su nasumični, a reprezentacija vremena u referentnom pamćenju promjenjiva i nejasna (Droit-Volet, 2016), što u kombinaciji s čestim gubitcima pozornosti (Karampela i sur., 2020) doprinosi povećanoj varijabilnosti u procjeni vremenskoga intervala.

Sa stajališta motoričke kontrole, teško je odoljeti spekulaciji da varijabilnost može djelomično proizaći iz pokušaja ispravljanja pogrešaka, čija je „cijena" povećana varijabilnost i ovisnost između intervala među odgovorima (Voillaume, 1971, citirano u Semjen i sur., 2000).

Navedeno se ne slaže sa stajalištem Lewis i Miall (2003), koji tajming u rasponu ispod sekunde podrazumijevaju „automatskim" te smatraju da se oslanja na kognitivnu kontrolu, štoviše, obično se smatra da kontinuacijska faza u Wing-Kristoffersonovu modelu djeluje u otvorenoj petlji (automatski način). Međutim, još uvijek je u tijeku rasprava, započeta još od Schmidta (1980) o uključenosti procesa povratnih informacija (engl. *feedback)* u motorički tajming. Tako su, na primjer, Madison i Delignières (2009) odredili 700-800 ms (i više) kao donju vremensku granicu koja dozvoljava ispravljanje pogreške, a koja se temelji na povratnim informacijama. S druge strane, u istraživanju koje je proveo Peters (1989) o ulozi trajanja intervala u svjesnoj percepciji, interval od 300 ms pojavio se kao granična točka u kojoj se pokreti iniciraju i doživljavaju pojedinačno. Možda je stoga moguće da su neki od ispitanika u ovom istraživanju vlastitu učestalost *tapinga* smatrali neadekvatnom u odnosu na zapamćeni tempo te su pokušaji promjene brzine rezultirali varijabilnijim izvedbama.

Rezultati dobiveni u ovom istraživanju u skladu su s opažanjem Aschersleben (2002) o sustavnoj pogrešci u *tapingu* koja se očituje tako da dodiri obično nekoliko desetaka milisekundi prethode nastupu signala, što se također naziva „negativna asinkronija" ili „greška sinkronizacije". Aschersleben (2002) pretpostavlja da se sinkronizacija uspostavlja na razini središnjih reprezentacija, dok je dodir u *tapingu* predstavljen svojim senzornim *feedbackom*, stoga negativna asinkronija, prema autorici, nastaje kao posljedica razlika u perifernom i/ili središnjem procesiranju vremena.

Zaključak

Wing-Kristoffersonov model (1973 a, b) omogućio je odvajanje komponenti procjenjivanja vremenskoga intervala te evaluaciju izvora varijabilnosti. Jasno je utvrđeno da centralna komponenta procjenjivanja pridonosi varijabilnosti IRI-a više od motoričke komponente zadatka. Djeca su se značajno razlikovala od mlađih odraslih u ukupnoj varijabilnosti, ali i u dekomponiranim komponentama varijabilnosti. Kao komparativna prednost ovoga istraživanja može se smatrati relativno veliki uzorak ispitanika, međutim, kao ograničenje i smjer za daljnje eksperimente, preporučuje se procjena uključenosti drugih srodnih konstrukata, kao što je npr. radno pamćenje i/ili uvrštavanje kapaciteta pozornosti.

Napomena i izvori financiranja

Istraživanje je potpomognuto financijskom potporom Sveučilišta u Zagrebu.

Autori zahvaljuju upravama te odgajateljicama (I. Kolarić, A. Sudec, M. Sakač, K. Apari i P. Radoš) iz dječjih vrtića na području gradova Ludbrega i Varaždina na pomoći prilikom provedbe mjerenja.