Archives of Physical Medicine and Rehabilitation

journal homepage: www.archives-pmr.org

Archives of Physical Medicine and Rehabilitation 2018;99:945-51

ORIGINAL RESEARCH

Rhythm Perception and Production Abilities and Their Relationship to Gait After Stroke

Kara K. Patterson, PT, PhD,[a,b,c] Jennifer S. Wong, MSc,[b] Svetlana Knorr, PT, PhD,[b] Jessica A. Grahn, PhD[d,e]

From the [a]Department of Physical Therapy, University of Toronto, Toronto, ON; [b]Toronto Rehabilitation Institute, University Health Network, Toronto, ON; [c]Rehabilitation Sciences Institute, University of Toronto, Toronto, ON; [d]Brain and Mind Institute, Western University, London, ON; and [e]Department of Psychology, Western University, London, ON, Canada.

Abstract

Objectives: To assess rhythm abilities, to describe their relation to clinical presentation, and to determine if rhythm production independently contributes to temporal gait asymmetry (TGA) poststroke.

Design: Cross-sectional.

Setting: Large urban rehabilitation hospital and university.

Participants: Individuals (N=60) with subacute and chronic stroke (n=39) and data for healthy adults extracted from a preexisting database (n=21).

Interventions: Not applicable.

Main Outcome Measures: Stroke group: National Institutes of Health Stroke Scale (NIHSS), Chedoke-McMaster Stroke Assessment (CMSA) leg and foot scales, Montreal Cognitive Assessment (MoCA), rhythm perception and production (Beat Alignment Test [BAT]), and spatiotemporal gait parameters were assessed. TGA was quantified with the swing time symmetry ratio. Healthy group: age and beat perception scores assessed by the BAT. Rhythm perception of the stroke group and healthy adults was compared with analysis of variance. Spearman correlations quantified the relation between rhythm perception and production abilities and clinical measures. Multiple linear regression assessed the contribution of rhythm production along with motor impairment and time poststroke to TGA.

Results: Rhythm perception in the stroke group was worse than healthy adults ($F_{1,56}=17.5$, $P=.0001$) Within the stroke group, rhythm perception was significantly correlated with CMSA leg (Spearman $\rho=.33$, $P=.04$), and foot (Spearman $\rho=.49$, $P=.002$) scores but not NIHSS or MoCA scores. The model for TGA was significant ($F_{3,35}=12.8$, $P<.0001$) with CMSA leg scores, time poststroke, and asynchrony of rhythm production explaining 52% of the variance.

Conclusions: Rhythm perception is impaired after stroke, and temporal gait asymmetry relates to impairments in producing rhythmic movement. These results may have implications for the use of auditory rhythmic stimuli to cue motor responses poststroke. Future work will explore brain responses to rhythm processing poststroke.

Archives of Physical Medicine and Rehabilitation 2018;99:945-51

When we hear music, we often feel the urge to tap along, and usually when we tap, we do not tap the rhythm itself, but instead we tap the beat (the steady, regularly spaced pulse perceived in music). This spontaneous synchronized movement may result from processing of the rhythm by motor areas in the brain.[1] Moreover, perception of a regular beat is specifically associated with activity in the supplementary motor area and the basal ganglia even when no movement is produced.[1] Rhythm abilities, including (1) the ability to perceive a beat in an auditory stimulus (eg, music) and (2) the ability to produce regular rhythmic movements (eg, tapping to the beat in music), are relevant to poststroke gait rehabilitation in 2 important ways: gait interventions that use rhythmic auditory cues and deviations in the gait pattern itself. One way to evaluate the abilities to perceive a

Presented in part to the International Society for Posture and Gait Research World Congress, June 30, 2015, Seville, Spain.

Supported by grants from the Heart and Stroke Foundation of Canada (grant no. 000216), the Canadian Partnership for Stroke Recovery, and a personnel award from the Heart and Stroke Foundation and Canadian Stroke Network.

Disclosures: none.

0003-9993/18/$36 - see front matter © 2018 by the American Congress of Rehabilitation Medicine

https://doi.org/10.1016/j.apmr.2018.01.009

beat and to produce a regular rhythmic movement is the Beat Alignment Test (BAT).[2] The BAT is comprised of 2 parts: the perception test requires the individual to judge whether tones superimposed over a music clip align with the beat of the music and the production test requires the individual to tap on a keyboard to the beat of a music clip.

Rhythmic auditory stimulation (RAS) is a gait intervention which involves walking to a rhythmic cue delivered by a metronome or music.[3] The mechanism through which RAS works lies in the extensive connectivity between the auditory and motor systems, which allows for entrainment between rhythmic auditory cues and motor responses.[1,4-8] A recent meta-analysis confirmed large effects sizes for the effect of RAS on velocity, cadence, and stride length in people with stroke.[9] Furthermore, some RAS studies reported improvement in important kinematic features (eg, knee flexion midswing)[10] and improvements in spatiotemporal parameters greater than those achieved with standard rehabilitation.[3,11] However, it is possible that despite improvements at the group level, there exists variation in responsiveness to RAS at the individual level. Individuals with stroke differ in their responsiveness to other gait interventions (eg, body weight−supported treadmill training, resistive cycling).[12,13] Furthermore there are some reports of nonresponders to RAS at the individual level in people with Parkinson disease.[14] One potential contributing factor to RAS responsiveness is rhythm perception. Even in individuals without neurologic conditions, there is variation in the ability to perceive the beat,[15] and this ability is related to responsiveness of gait to rhythmic auditory stimuli. For example, young adults classified as weak perceivers based on their performance on the BAT, walked slower and with shorter steps during RAS, whereas young adults who performed better on the BAT, classified as strong perceivers, maintained their gait pattern.[16] For weak perceivers, attempting to synchronize steps to a cue might be an attention-demanding task that slows and shortens strides, negatively affecting responsiveness to RAS.[16] We propose that weak rhythm perception may contribute to diminished responsiveness to RAS in people with stroke as well. Before investigating responsiveness to RAS poststroke, an important first step is to describe rhythm perception poststroke.

Another important reason for investigating rhythm abilities is related to the temporal asymmetry of gait exhibited by >55% of individuals with stroke.[17-19] Symmetric gait is often a target of rehabilitation, possibly because persisting asymmetry is linked to long-term consequences (eg, challenges to balance control, joint pain and degeneration, bone density loss, gait inefficiencies).[20-23] Unfortunately, temporal gait asymmetry (TGA) appears resistant to intervention.[24] For example, a longitudinal study of individuals admitted to an inpatient stroke rehabilitation program revealed a significant increase in gait velocity at discharge but no change in TGA.[19] It is our view that resistance of TGA to intervention is related to lack of specificity of some gait training programs rather than a reflection of incapacity for change; however, there has been little direct investigation on the matter. Other concerns include the fact that TGA may be more severe during daily walking than walking observed in the laboratory[25] and additionally TGA may worsen over time.[26,27] Development of new interventions that train symmetric gait will depend on a deeper understanding of the mechanisms underlying TGA. A common assumption is that TGA is caused by the unilateral nature of poststroke motor impairments. Indeed, gait asymmetry relates to motor impairment[17] but it does not fully explain TGA. For example, individuals with good motor recovery who walk quickly do not necessarily walk symmetrically.[17] Investigation of other factors contributing to TGA, outside the obvious ones, is necessary. One such factor may be impaired rhythm production.

Healthy gait features regular, reciprocal leg movement and therefore has an inherent rhythm. TGA can be described as having an uneven or impaired rhythm. Previous work suggests a neuroanatomic link between rhythm abilities and TGA; injury to the posterolateral putamen was 60% to 80% more likely in poststroke individuals with TGA than those without TGA.[28] In addition, a case report provided evidence of a man with ischemic stroke (right temporal lobe, capsular and basal ganglia lesions) who could reproduce individual rhythms, but could not tap a steady beat to either a metronome or marching band music.[29] Therefore, there is both neuroimaging and neuropsychological evidence that the ability to perceive and produce irregular temporal patterns dissociates from the ability to perceive and produce an underlying beat, and in several cases, damage to or dysfunction of the basal ganglia was implicated. Given the involvement of putamen in TGA, beat production abilities may be impaired after stroke and these impairments may prevent individuals from producing a regular, steady gait pattern.

Knowledge about rhythm abilities poststroke will expand our understanding and guide future investigations of poststroke TGA. Such knowledge may also guide adaptations to improve existing gait interventions (ie, RAS), or inform the development of new interventions. Therefore, the objectives of this study were (1) to characterize rhythm abilities after stroke, (2) to describe the relation of rhythm abilities to clinical presentation poststroke, and (3) to determine if rhythm production independently contributes to TGA poststroke.

List of abbreviations:

ANOVA	**analysis of variance**
BAT	**Beat Alignment Test**
CMSA	**Chedoke-McMaster Stroke Assessment**
MoCA	**Montreal Cognitive Assessment**
NIHSS	**National Institutes of Health Stroke Scale**
RAS	**rhythmic auditory stimulation**
TGA	**temporal gait asymmetry**

Methods

Participants

A cross-sectional study was conducted with data collected from people with stroke in a single visit. Participants with stroke were recruited from an urban rehabilitation hospital and the surrounding community. Inclusion criteria included (1) first occurrence of stroke and (2) ability to walk 10m without physical assistance or gait aid. Exclusion criteria included (1) history of other neurologic conditions that influence gait (eg, Parkinson disease) and (2) hearing impairment beyond what can be corrected with devices. This study was approved by the University Health Network Research Ethics Board, and all participants provided informed, written consent.

Data related to age and rhythm perception were extracted from a preexisting dataset of healthy older adults (n=21) who were tested on the same perception portion of the BAT used in this study. These participants were originally tested in a study comparing beat perception ability in older adults and patients with Parkinson disease; therefore, beat production scores were not available.[30]

Testing protocol for participants with stroke

Clinical assessment

Clinical presentation was characterized with performance-based measures administered by a research assistant. Stroke severity was measured with the National Institutes of Health Stroke Scale (NIHSS), which is a valid and reliable measure with larger values indicating greater severity of stroke-related impairments.[31] The Chedoke-McMaster Stroke Assessment (CMSA) was used to measure motor impairment of the leg and foot. The CMSA leg and foot scales are each measured with a 7-point scale, and smaller scores indicate greater motor impairment.[32] Cognitive impairment was measured with the Montreal Cognitive Assessment (MoCA),[33] and smaller scores indicate greater cognitive impairment.

Spatiotemporal gait assessment

Overground, self-paced gait was assessed with a pressure sensitive mat (495×86×0.4cm) that recorded spatiotemporal parameters.[a] Participants walked across the mat without any physical assistance or gait aids for 2 trials, which allowed an adequate number of footfalls to ensure confidence in the measures without fatiguing the participants.[34] Participants began and ended each walking trial 1m away from the mat so that only steady-state gait was collected. Participants were instructed to walk at their preferred pace across the mat and to not alter their walking pattern to adjust to the mat.

Rhythm abilities assessment

The abilities to perceive and produce a regular beat were measured with the BAT from the Goldsmiths Musical Sophistication Index v1.0[2] administered with a laptop computer.[1] For the perception task, participants heard musical stimuli over the laptop speakers. The task required participants to discriminate a series of tones overlaid on the music. Participants were asked to answer yes or no to the question "Are the tones on the beat of the music?" For the production task, participants were required to tap to the beat of musical stimuli with the unaffected hand on the spacebar of the laptop keyboard.

Data processing

Spatiotemporal gait parameters

The manufacturer's software that accompanies the pressure sensitive mat automatically identifies footfalls that can subsequently be manually edited. Each walking trial was visually inspected, and footfalls that were partially off either end of the mat were removed from analysis. Spatiotemporal parameters were then calculated by the manufacturer's software. Spatiotemporal parameters were averaged over the 2 walking trials, and mean values were used in subsequent data analysis. TGA was quantified per recommendations with the swing ratio (ratio of the mean left and right swing times with the larger value in the numerator).[18]

Rhythm abilities

BAT perception task performance was expressed as accuracy (percentage of correct responses). BAT production performance was expressed as asynchrony, which is the difference (milliseconds) on average between the beat times in the music presented to participant and their tap times on the keyboard. The timing of the spacebar key presses was measured using E-Prime 2.0,[b] which has millisecond-level accuracy. The participant's tap times were matched to the nearest beat time in the music, and the absolute value of the difference between the tap time and the nearest beat time was calculated. Therefore, asynchrony represents the average amount a participant's tapping is off the beat, with lower scores (less asynchrony) representing more accurate performance.

Statistical analyses

All statistical analyses were performed with SAS 9.3.[c] The mean ± SD values of all demographic, clinical, gait, and rhythm variables were calculated for the stroke group, and the mean ± SD values for rhythm perception scores were calculated for the healthy adults.

Objective 1: rhythm abilities poststroke

Descriptive statistics were used to characterize performance on the BAT in people with stroke. To determine if people with stroke exhibit impaired rhythm perception, a 1-way analysis of variance (ANOVA) was used to compare perception accuracy scores in the stroke group with scores in the group of healthy adults. Similarity in age between the 2 groups was also checked with a 1-way ANOVA to rule out the effects of ageing as a potential cause of impaired rhythm perception poststroke. Unequal sample sizes between the stroke and healthy adults for the ANOVAs were accounted for by using type III sum of squares, which has been recommended for unbalanced data.[35] Significance was set at $P=.05$.

Objective 2: relation of rhythm abilities to clinical presentation poststroke

The relation between rhythm production and perception and the relation of both perception and production with clinical characteristics (ie, NIHSS, CMSA, and MoCA scores) within the stroke group were explored with Spearman correlations. Spearman correlations were used because we expected variables to covary and some of the variables were ordinal.[36] Significance was set at $P=.05$.

Objective 3: contribution of rhythm production to TGA poststroke

Linear multiple regression was run to determine the independent contribution of rhythm production ability to TGA poststroke. Leg motor impairment and time poststroke were also included in the model as independent variables because both factors have a positive relation with severity of TGA.[17,26,27] Significance was set at $P=.05$.

Results

Participants with stroke

Thirty-nine participants with stroke participated. Nineteen participants were <6 months poststroke and 20 were ≥6 months poststroke. The clinical characteristics, TGA, and rhythm abilities of the participants with stroke are summarized in table 1. All individuals in the stroke group successfully performed the walking trials without a gait aid. Data were missing from participants with stroke for the following variables: perception (n=1), NIHSS score (n=1), and MoCA score (n=4). These individuals were excluded from any analysis that involved those variables. The mean age of the stroke group was 63.3±11.7 years, which was not significantly different from the group of older adults in the preexisting database (65.0±7.9y; $P=.56$).

Table 1 Clinical characteristics, TGA, and rhythm abilities

Variable	Stroke Group (n=39)
Age	63.3±11.7 (59.5–67.1)
Sex (F/M)	20/19
Months poststroke	40.8±64.6 (19.8–61.7)
Affected side (R/L)	15/24
NIHSS score (0–42)	2.7±1.8 (2.1–3.3)
CMSA leg score (0–7)	5.6±1.0 (5.2–5.9)
CMSA foot score (0–7)	4.8±1.5 (4.4–5.3)
MoCA score (0–30)	24.7±4.1 (23.2–26.1)
Swing ratio	1.18±0.22 (1.11–1.26)
Perception (% correct)	57.0±16.7 (51.6–62.5)
Asynchrony (ms)	103.3±12.2 (99.3–107.3)

NOTE. Values are mean ± SD (95% confidence interval) or n.
Abbreviations: F, female; L, left; M, male; R, right.

Objective 1: rhythm abilities poststroke

Within the stroke group, beat perception accuracy was not significantly correlated with beat production asynchrony (Spearman $\rho=-.27$, $P=.10$). The stroke group scored significantly lower on the beat perception component of the BAT than the healthy group ($F_{1,56}=17.52$, $P=.0001$) (fig 1).

Objective 2: relation between rhythm abilities and clinical presentation poststroke

Beat perception in the stroke group significantly correlated with CMSA leg (Spearman $\rho=.33$, $P=.04$) and foot (Spearman $\rho=.49$, $P=.002$) scores but not NIHSS (Spearman $\rho=-.11$, $P=.50$) or MOCA scores (Spearman $\rho=$ .21, $P=.22$) (fig 2). Asynchrony of beat production was not significantly correlated with any clinical measure (all $P>.15$).

Objective 3: contribution of rhythm production to TGA poststroke

The results of linear multiple regression analysis are summarized in table 2. The model for TGA was significant ($F_{3,35}=12.76$, $P<.0001$, $R^2=.52$).

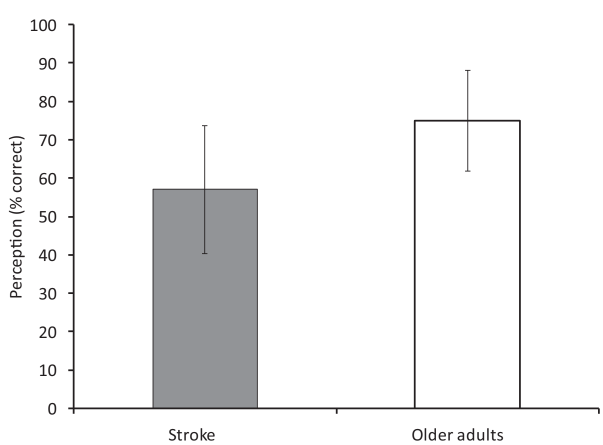

Fig 1 Rhythm perception. Mean accuracy on the rhythm perception test for healthy (open bar) and stroke (shaded bar) groups. Error bars represent SD. The scores were significantly different ($P=.0001$).

Discussion

The main findings of this study are that rhythm perception is impaired after stroke compared with healthy older adults, and impaired rhythm production ability is related to TGA poststroke. In this study, beat perception performance measured by the BAT significantly correlated with measures of lower extremity motor impairment. Motor areas such as the basal ganglia and supplementary motor area have been linked to rhythm abilities,[29,37] and it is possible that stroke-related damage to these areas resulted in both motor impairment of the lower extremity and impaired rhythm perception in the current study group. It is unlikely that the observed poor beat perception can be attributed to general stroke severity or a lack of understanding of how to complete the BAT because test performance was not related to either NIHSS or MoCA scores.

In this study, Spearman correlations revealed that rhythm perception ability was not associated with rhythm production ability. This differs from the general finding with neurologically intact individuals that performance on rhythm perception and production tasks are highly correlated.[38,39] However, even in this previous work, there are individuals who perform very poorly on either perception, or production, but not both. Therefore, although not unique, the dissociation of rhythm perception from production in patients with stroke appears to be more common than in the general population.

Our results provide preliminary support for the hypothesis that TGA is in part attributable to impaired rhythm production ability poststroke. Asynchrony of rhythmic tapping was associated with TGA independent of time poststroke and motor impairment of the leg. However, it appears that TGA decreases as asynchrony of beat production increases, which is opposite of what was expected. The reasons for this are unknown, and this study is not designed to answer this question. Further investigation of this relation between rhythm production and the gait pattern poststroke is warranted.

Our results are relevant to work that uses auditory rhythmic stimuli to cue motor performance poststroke. There is strong evidence that RAS improves key spatiotemporal[9] and kinematic[10] variables poststroke and that these improvements are greater than those achieved with standard rehabilitation.[3,9,11] Unfortunately, TGA seems less responsive to RAS, with individuals demonstrating 39% change compared with a 128% change in velocity.[11] Moreover, the mean swing ratio achieved after RAS (1.72) is still considered grossly asymmetric compared with the normative cutoff point (1.06).[18] The present results suggest a potential explanation for this. Most theories of RAS mechanisms suggest that the external cue compensates for a deficient internal timing mechanism; therefore, matching step timing to the cue is thought to be an important element of the intervention.[40] Some individuals poststroke may be unable to perceive the steady beat of the auditory cue and/or produce a regular rhythmic stepping response and therefore may not be as responsive to the RAS cue. This argument assumes that the benefit of RAS comes from matching steps to the cue; however, people with stroke could benefit simply from a cue to step faster, even if they are unable to match their step to the beat. Future work should investigate the relation between rhythm abilities and responsiveness to RAS in individuals with poststroke TGA and determine whether improvements are enhanced when footfalls are matched correctly to the cue. Another interesting and related avenue to pursue is whether rhythm abilities can improve with training poststroke and whether this translates into improved gait rhythmicity and/or greater responsiveness to RAS.

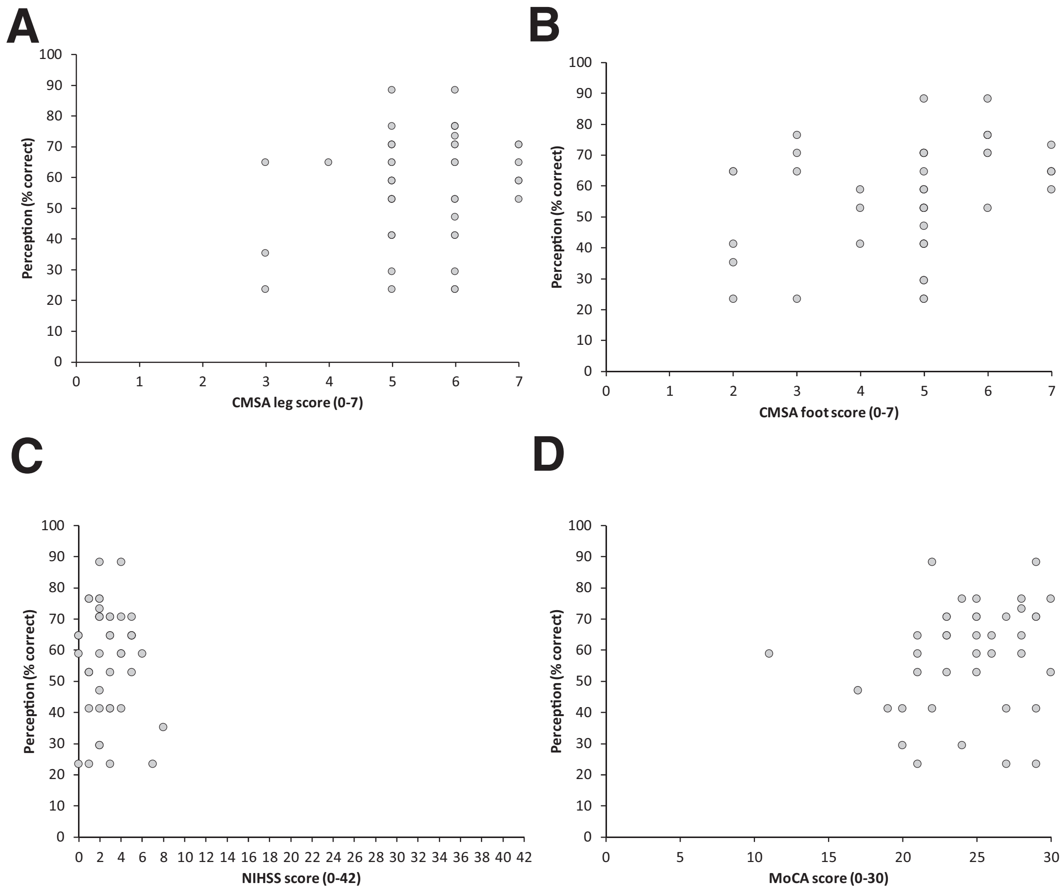

Fig 2 Relations between motor and cognitive impairment and rhythm abilities. Beat perception in the stroke group significantly correlated with CMSA scores for the leg (A) and foot (B) (both $P<.05$) but not scores on the NIHSS (C) or MoCA (D).

Study limitations

This study has some limitations. First, on average, the stroke group exhibited mild to moderate motor impairment, and all individuals could walk without a gait aid. Therefore, the results likely cannot be generalized to those with more severe motor impairment and less independent walking function. Second, characterization of the stroke lesion with imaging was not available. Third, an adult control group that completed the full protocol was not included. We would not expect individuals without neurologic impairment to exhibit TGA[41] nor would we expect them to show significant deficits on the clinical measures (ie, CMSA, MoCA); therefore, an adult control group would not have been used in the correlation or linear regression analyses. However, it would have been informative to have the production scores on the BAT for comparison. Future work will recruit individuals with a wider range of motor deficits and investigate both lesion characteristics and brain activity associated with rhythm abilities with magnetic resonance imaging in comparison with age-matched adults without stroke.

Conclusions

The ability to perceive a beat in an auditory stimulus is impaired poststroke, and impaired rhythm production ability may be

Table 2 Results of multiple regression analysis

Measure	Model R^2	Model P	Parameter Estimate	t	P
Swing time symmetry	.52	<.0001			
Intercept			2.15	7.06	<.0001
CMSA leg			−0.09	−3.57	.001
Rhythm production asynchrony			−0.005	−2.17	.04
Time poststroke			0.001	2.91	.006

NOTE. The model for swing time symmetry was tested using CMSA leg score, time poststroke, and rhythm production asynchrony as independent variables.

another factor contributing to TGA poststroke. This information can inform future investigations into the underlying mechanisms of TGA and the development of gait rehabilitation interventions to address TGA.

Suppliers

a. GAITRite; CIR Systems.
b. E-Prime version 2.0; Psychology Software Tools.
c. SAS version 9.3; SAS Institute.

Keywords

Gait; Perception; Rehabilitation; Stroke

Corresponding author

Kara K. Patterson, PT, PhD, University of Toronto, 160-500 University Ave, Toronto, ON M5G 1V7, Canada. *E-mail address:* kara.patterson@utoronto.ca.

References

1. Grahn JA, Brett M. Rhythm and beat perception in motor areas of the brain. J Cogn Neurosci 2007;19:893-906.
2. Mullensiefen D, Gingras B, Musil J, Stewart L. The musicality of non-musicians: an index for assessing musical sophistication in the general population. PLoS One 2014;9:e89642.
3. Thaut MH, McIntosh GC, Rice RR. Rhythmic facilitation of gait training in hemiparetic stroke rehabilitation. J Neurol Sci 1997;151:207-12.
4. Thaut MH, Abiru M. Rhythmic auditory stimulation in rehabilitation of movement disorders: a review of current research. Music Perception: An Interdisciplinary Journal 2010;27:263-9.
5. Chen JL, Zatorre RJ, Penhune VB. Interactions between auditory and dorsal premotor cortex during synchronization to musical rhythms. Neuroimage 2006;32:1771-81.
6. Zatorre RJ, Chen JL, Penhune VB. When the brain plays music: auditory-motor interactions in music perception and production. Nat Rev Neurosci 2007;8:547-58.
7. Chen JL, Penhune VB, Zatorre RJ. Moving on time: brain network for auditory-motor synchronization is modulated by rhythm complexity and musical training. J Cogn Neurosci 2008;20:226-39.
8. Grahn JA, Rowe JB. Feeling the beat: premotor and striatal interactions in musicians and nonmusicians during beat perception. J Neurosci 2009;29:7540-8.
9. Yoo GE, Kim SJ. Rhythmic auditory cueing in motor rehabilitation for stroke patients: systematic review and meta-analysis. J Music Ther 2016;53:149-77.
10. Shin YK, Chong HJ, Kim SJ, Cho SR. Effect of rhythmic auditory stimulation on hemiplegic gait patterns. Yonsei Med J 2015;56:1703-13.
11. Thaut MH, Leins AK, Rice RR, et al. Rhythmic auditory stimulation improves gait more than NDT/Bobath training in near-ambulatory patients early poststroke: a single-blind randomized trial. Neurorehabil Neural Repair 2007;21:455-9.
12. Bowden MG, Behrman AL, Neptune RR, Gregory CM, Kautz SA. Locomotor rehabilitation of individuals with chronic stroke: difference between responders and nonresponders. Arch Phys Med Rehabil 2013;94:856-62.
13. Mulroy SJ, Klassen T, Gronley JK, Eberly VJ, Brown DA, Sullivan KJ. Gait parameters associated with responsiveness to treadmill training with body-weight support after stroke: an exploratory study. Phys Ther 2010;90:209-23.
14. McIntosh GC, Brown SH, Rice RR, Thaut MH. Rhythmic auditory-motor facilitation of gait patterns in patients with Parkinson's disease. J Neurol Neurosurg Psychiatry 1997;62:22-6.
15. Grahn JA, McAuley JD. Neural bases of individual differences in beat perception. Neuroimage 2009;47:1894-903.
16. Leow LA, Parrott T, Grahn JA. Individual differences in beat perception affect gait responses to low-and high-groove music. Front Hum Neurosci 2014;8:811.
17. Patterson KK, Parafianowicz I, Danells CJ, et al. Gait asymmetry in community-ambulating stroke survivors. Arch Phys Med Rehabil 2008;89:304-10.
18. Patterson KK, Gage WH, Brooks D, Black SE, McIlroy WE. Evaluation of gait symmetry after stroke: a comparison of current methods and recommendations for standardization. Gait Posture 2010;31:241-6.
19. Patterson KK, Mansfield A, Biasin L, Brunton K, Inness EL, McIlroy WE. Longitudinal changes in post-stroke spatiotemporal gait asymmetry over inpatient rehabilitation. Neurorehabil Neural Repair 2015;29:153-62.
20. Teasell RW, Bhogal SK, Foley NC, Speechley MR. Gait retraining post stroke. Top Stroke Rehabil 2003;10:34-65.
21. Lewek MD, Bradley CE, Wutzke CJ, Zinder SM. The relationship between spatiotemporal gait asymmetry and balance in individuals with chronic stroke. J Appl Biomech 2013;30:31-6.
22. Jorgensen L, Crabtree NJ, Reeve J, Jacobsen BK. Ambulatory level and asymmetrical weight bearing after stroke affects bone loss in the upper and lower part of the femoral neck differently: bone adaptation after decreased mechanical loading. Bone 2000;27:701-7.
23. Ellis RG, Howard KC, Kram R. The metabolic and mechanical costs of step time asymmetry in walking. Proc Biol Sci 2013;280:20122784.
24. Patterson SL, Rodgers MM, Macko RF, Forrester LW. Effect of treadmill exercise training on spatial and temporal gait parameters in subjects with chronic stroke: a preliminary report. J Rehabil Res Dev 2008;45:221-8.
25. Prajapati SK, Gage WH, Brooks D, Black SE, McIlroy WE. A novel approach to ambulatory monitoring: investigation into the quantity and control of everyday walking in patients with subacute stroke. Neurorehabil Neural Repair 2011;25:6-14.
26. Turnbull GI, Wall JC. Long-term changes in hemiplegic gait. Gait Posture 1995;3:258-61.
27. Patterson KK, Gage WH, Brooks D, Black SE, McIlroy WE. Changes in gait symmetry and velocity after stroke: a cross-sectional study from weeks to years after stroke. Neurorehabil Neural Repair 2010;24:783-90.
28. Alexander LD, Black SE, Patterson KK, Gao F, Danells CJ, McIlroy WE. Association between gait asymmetry and brain lesion location in stroke patients. Stroke 2009;40:537-44.
29. Fries W, Swihart AA. Disturbance of rhythm sense following right hemisphere damage. Neuropsychologia 1990;28:1317-23.
30. Cameron DJ, Pickett KA, Earhart GM, Grahn JA. The effect of dopaminergic medication on beat-based auditory timing in Parkinson's disease. Front Neurol 2016;7:19.
31. Brott T, Adams HP Jr, Olinger CP, et al. Measurements of acute cerebral infarction: a clinical examination scale. Stroke 1989;20:864-70.
32. Gowland C, VanHullenaar S, Torresin W. Chedoke-McMaster Stroke Assessment: development, validation and administration manual. Hamilton: McMaster University; 1995.
33. Nasreddine ZS, Phillips NA, Bedirian V, et al. The Montreal Cognitive Assessment, MoCA: a brief screening tool for mild cognitive impairment. J Am Geriatr Soc 2005;53:695-9.
34. Wong JS, Jasani H, Poon V, Inness EL, McIlroy WE, Mansfield A. Inter-and intra-rater reliability of the GAITRite system among individuals with sub-acute stroke. Gait Posture 2014;40:259-61.

35. Shaw RG, Mitchell-Olds T. ANOVA for unbalanced data: an overview. Ecology 1993;74:1638-45.
36. McDonald JH. Handbook of biological statistics. Vol 2. Baltimore: Sparky House Publishing; 2009.
37. Grahn JA, Schuit D. Individual differences in rhythmic ability: behavioral and neuroimaging investigations. Psychomusicology: Music, Mind, and Brain 2012;22:105-21.
38. Cameron DJ, Grahn JA. Enhanced timing abilities in percussionists generalize to rhythms without a musical beat. Front Hum Neurosci 2014;8:1003.
39. Sowiński J, Dalla Bella S. Poor synchronization to the beat may result from deficient auditory-motor mapping. Neuropsychologia 2013;51:1952-63.
40. Nombela C, Hughes LE, Owen AM, Grahn JA. Into the groove: can rhythm influence Parkinson's disease? Neurosci Biobehav Rev 2013;37:2564-70.
41. Patterson KK, Nadkarni NK, Black SE, McIlroy WE. Gait symmetry and velocity differ in their relationship to age. Gait Posture 2012;35:590-4.