The Development of Biological Motion Processing in Childhood through Early Adolescence: Examining the Role of Dynamic Attention and Implications for Social Competence

Emily Stubbert, M.A.

Department of Educational and Counselling Psychology

McGill University

Montreal, QC.

November 2023

A thesis submitted to McGill University in partial fulfillment of the requirements for the degree of Doctor of Philosophy in School/Applied Child Psychology

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Abstract

The ability to accurately process biological motion, the movement of living organisms, is a foundational skill for navigating and interacting with the real-world environment. Attending to and interpreting biological motion is thought to be an underlying mental operation of effective social communication and interactions with other people. The ability to simply detect the presence of biological motion appears to be uniquely reflexive, seemingly due to a bias for socially relevant information, and develops relatively quickly during infancy. However, under more complex and ambiguous conditions, such as those in the real-world environment, biological motion processing appears to require effortful controlled attentional processing and may follow a longer developmental trajectory, continuing through childhood and adolescence. The main goal of the two manuscripts in this dissertation is to explore the development of biological motion processing, specifically in terms of a) the role of attentional processing and b) the link to real-world social processing and behaviour between childhood and early adolescence. To obtain a more nuanced understanding of the contributing factors for the development of biological motion processing, 49 children and adolescents (24 males) aged 6 to 14 years completed a 3-dimentional (3D) masked direction discrimination point light walker biological motion task. In the 1st manuscript, we explored possible contributions of dynamic attention by examining the developmental relationship between performance on the 3D biological motion task and that on a 3D version of the multiple object tracking (MOT) task. The findings revealed that performance on both tasks improved similarly with age, suggesting comparable developmental trajectories between the two tasks. In the 2nd manuscript, the social perceptual component of biological motion processing was examined with an emphasis on the extent to which the performance on the 3D task predicted real-world social competence, as indicated by parent ratings on the

Multidimensional Social Competence Scale. Contrary to our hypothesis, the multiple regression analyses revealed that performance on the biological motion task did not predict social competence. Overall, these findings suggest that the developmental trajectory of performance on biological motion task into adolescence may be largely attributable to the more general development of dynamic visual attention. And, whereas biological motion may be considered a hallmark of social cognition, the link between biological motion processing and real-world socially competent behaviour is complex and needs to be further explored.

Résumé General

La capacité de traiter avec précision le mouvement biologique, c'est-à-dire le mouvement des organismes vivants, est une compétence fondamentale pour naviguer et interagir avec l'environnement réel. L'attention portée au mouvement biologique et son interprétation sont considérées comme une opération mentale sous-jacente à une communication sociale et aux interactions efficaces avec les autres personnes. La capacité à simplement détecter la présence de mouvements biologiques semble être unique et réflexive, probablement en raison d'un biais pour l'information socialement pertinente, et se développe relativement rapidement pendant la petite enfance. Cependant, dans des conditions plus complexes et ambiguës, telles que celles de l'environnement réel, le traitement du mouvement biologique semble nécessiter un traitement attentionnel contrôlé et exigeant, et peut suivre une trajectoire de développement plus longue, se poursuivant tout au long de l'enfance et de l'adolescence. L'objectif principal des deux études de cette dissertation est d'explorer le développement du traitement du mouvement biologique, notamment en termes de a) le rôle du traitement attentionnel et b) le lien avec le traitement social et le comportement réel pendant la période de l'enfance et de l'adolescence. Pour obtenir une compréhension plus nuancée des facteurs contribuant au développement du traitement du mouvement biologique, 49 enfants et adolescents (24 garçons) âgés de 6 à 14 ans ont réalisé une tâche de traitement du mouvement biologique de marcheur à points de lumière masquée tridimensionnelle (3D). Dans le premier article, nous avons exploré les contributions possibles de l'attention dynamique en examinant la relation développementale entre la performance à la tâche de mouvement biologique 3D et celle d'une version 3D de la tâche de suivi d'objets multiples. Les résultats ont révélé que la performance aux deux tâches s'est améliorée de manière similaire avec l'âge, suggérant des trajectoires développementales comparables entre les deux tâches. Dans le deuxième article, la composante perception sociale du traitement du mouvement biologique a été examinée en mettant l'accent sur la mesure dans laquelle la performance à la tâche 3D prédisait la compétence sociale réelle, comme indiquée par les évaluations des parents sur une échelle de compétence sociale multidimensionnelle. Contrairement à notre hypothèse, les analyses de régression multiples ont révélé que la performance à la tâche de mouvement biologique ne prédisait pas la compétence sociale. Dans l'ensemble, ces résultats suggèrent que la trajectoire de développement de la performance à la tâche de mouvement biologique à l'adolescence peut être largement attribuable au développement plus général de l'attention visuelle dynamique. Alors que le mouvement biologique peut être considéré comme une marque distinctive de la cognition sociale, le lien entre le traitement du mouvement biologique et le comportement socialement compétent dans le monde réel est complexe et nécessite d'être exploré davantage.

Acknowledgements

This dissertation would not have been possible without the encouragement, support, collaboration, and inspiration from countless individuals. I would like to begin by thanking my research supervisor, Dr. Jacob Burack, for the guidance and support that he has given me since he graciously accepted me into the McGill Youth Study Team (MYST) family in fall 2014. Thank you for all of the opportunities you have offered me and the immense knowledge that you have shared. I would like to also extend thanks to Dr. Armando Bertone, who has been such an integral mentor and collaborator throughout this process. Thank you for always accepting my impromptu “I need help” ambushes with positivity and a friendly smile. Dr. Domenico Tullo, thank you for sharing your expertise on the MOT task, your statistical knowledge, and your insights into navigating the dissertation and publication process, all of which you offered with such patience and kindness. Thank you to Dr. Jocelyn Faubert for creating such a unique and useful experimental task, and for your insight and contributions to the manuscripts. To my thesis committee member and clinical supervisor, Dr. Eve-Marie Quintin, thank you for sharing your insight, and always offering a listening ear and the accountability that I needed to continue moving forward. Additionally, I am grateful to the professors of the School/Applied Child Psychology program for teaching me to become a critical thinker and encouraging me to be a scientist-practitioner throughout this degree.

Moving to Montreal from the comfort of my little hometown was challenging, but the members of my cohort and those above and below mine in the School/Applied Child Psychology (SACP) program helped me not only survive the transition but also made Montreal feel like a second home. In this program I was lucky enough to find some of my best friends. To Emma Clark and Sam O’Brien, I would not have survived this process without you. Your friendship

offered me the perfect balance of encouragement, accountability, motivation, love, dancing, pizza, and Sangria to help carry me to this finish line and I am forever grateful. To Sarah Alati, Janet Amos, Micah Tilley, Loredana Marchica, and Catherine Archambeau, thank you for adding joy to this journey and memories that I will never forget. I have also been so blessed to have had some of my dearest classmates become colleagues – Ida Foster, Joe D'Intino, Mike Clyde, and Ivana DiLeo, I look forward to working with you in the future, especially when I am no longer a "re-educator".

I would like to thank all the members of the MYST lab, past and present, including Johanna, Jessica, William, Jordyne, Olivia, Margarita, and the many others who helped collect the data for this project. Thank you all for your time, support, and patience, and for humoring me with your participation in my MYST holiday parties both in person and virtually. A special thanks to Dr. Vanessa Weva and Dr. Jenilee Napoleon who were a never-ending source of encouragement along the way. Your dedication, professionalism, and fierce commitment to succeeding has been so inspirational.

Lastly, I could not have completed this graduate school journey without the support of my family. To my parents, Jeff and Kathryn, thank you for the never-ending love, encouragement and the countless sacrifices you have made for me as I pursued my dream of being a psychologist – even though it meant me moving away from you. You have taught me the importance of hard work and dedication which has helped me achieve all that I have thus far. To my husband, Nathan, your patience, love and encouragement throughout my doctoral studies have been unwavering, even during the toughest days, and I would not have made it through without you. I cannot wait to see what life has to hold for us when I am no longer a student. To the rest of my family, your love, understanding, and belief in me have been a driving force behind my accomplishments and I am truly blessed to have you all by my side.

Contribution of Original Knowledge

The present dissertation includes several original contributions. Overall, the findings add to our understanding of the factors contributing to the development of biological motion processing during childhood through early adolescence and highlight the role of dynamic attention. Specific to Manuscript 1, this is the first study in which biological motion and multiple object tracking (MOT) performance are examined concurrently, allowing for an understanding of the impact of the nature of the information to which attention is directed. The finding that performance improved between 6 and 14 years of age also provides additional empirical evidence to support the notion that biological motion processing continues to develop beyond the infant years. Manuscript 2 is the first study of the predictive value of biological motion performance and the Multidimensional Scale of Social Competence (Yager & Iarocci, 2013), a validated caregiver report that captures aspects of social functioning that are skill-based and multidimensional. Although no relationship was found between these measures, the findings suggest that the essential contribution of dynamic attention biological motion tasks should be considered in order to better illustrate the real-world social implications of the perception of this motion.

Author Contributions

I, Emily Stubbert, am the primary author of both manuscripts included in this dissertation. As such, I conceptualized and developed each study, and co-authors provided support when needed. Drs. Jacob A. Burack and Armando Bertone were co-authors for both studies. As my doctoral supervisor and project collaborator respectively, they advised me in the conceptualization and development of research questions, aided in finalizing experimental paradigm parameters, and provided feedback and edits. Dr. Domenico Tullo assisted with the statistical analyses and interpretation of the results for both studies. For manuscript 2, Karen Arias assisted with the review of the literature and manuscript editing. Dr. Jocelyn Faubert designed the 3D MOT and biological motion tasks, and provided expertise to interpret the results. The first manuscript has been published in *Cognitive Development.*

This research was funded by a doctoral scholarship from the Fonds de Recherche du Quebec – Société et culture (FRQSC) awarded to Emily Stubbert, as well as a Social Sciences and Humanities Research Council (SSHRC) Insight grant awarded to Drs. Bertone and Burack.

List of Tables and Figures

Literature Review

Manuscript 1

Manuscript 2

List of Abbreviations

2D / 3D - Two-dimensional / Three-dimensional
ADOS-2 - Autism Diagnostic Observation Schedule – Second Edition
ADHD – Attention Deficit / Hyperactivity Disorder
ANOVA - Analysis of Variance
ANT - Attention Network Task
APA - American Psychiatric Association
ASD - autism spectrum disorder
AQ - Autism-Spectrum Quotient
BAE - Body Action Evaluator
BM - Biological Motion
CARS - Conners Autism Rating Scale
CPT-3 - Continuous Performance Task – Third edition
CSCS - Children's Social Competence Scale
EQ – Empathy Quotient
FSIQ - Full Scale Intelligence Quotient
HDTV - High-Definition Television
IQ - Intelligence Quotient
KCPT-2 - Kiddie Continuous Performance Task – Second Edition
MOT - Multiple Object Tracking
MSCS - Multidimensional Scale of Social Competence
PLD - Point Light Display
PRI – Perceptual Reasoning Index
RMET – Reading the Mind in the Eyes Test
SCQ - Social Communication Questionnaire
SRS-2 - Social Responsiveness Scale – Second Edition
TD - Typically Developing
VCI – Verbal Comprehension Index
WASI-II - Wechsler's Abbreviated Scale of Intelligence – Second Edition

Chapter I: Introduction

During the school years, social competence is one of the primary skills to be developed both in the classroom and at home with support from teachers and parents (Arnold & Lindner-Müller, 2012; Junge et al., 2020). The social skills needed to interact competently with those in their environment include detecting and interpreting the actions of others in order to respond in an adaptive manner. One foundational socio-cognitive skill of this type is the processing of biological motion, which includes whole-body global motion as well as the local motion of individual body parts (i.e., hands, head, and arms). This perception of the dynamic natural environment is essential for inferring intent from the actions of others (Thompson & Parasuraman, 2012). The ability to perceive and understand others' movements and gestures is thought to serve many evolutionary purposes necessary for survival, such as an infant's recognition of the primary caregiver who feeds and protects, thereby facilitating social bonding (Weisman et al., 2013). Biological motion processing also allows for the interpretation of non-verbal communication which is particularly important during early stages of development when such skills are limited. Later in development, perceiving and understanding how people move allows children and adolescents to anticipate future behaviour and adjust their own actions accordingly to effectively interact with their peers.

Biological motion processing has traditionally been considered to be a relatively primitive and reflexive function (e.g., Simion et al., 2011; Thornton et al., 2002), evidenced by the ability to detect and discriminate biological motion being adult-like by 5 years of age (Pavlova et al., 2001). However, the necessity of the top-down influence of attention in the processing of biological motion has been highlighted, particularly when stimuli are ambiguous, degraded, or overlap one another (Stehr et al., 2021; Thompson & Parasuraman, 2012; Thornton

& Vuong, 2004). Thus, under more complex and ambiguous conditions, the ability to process biological motion improves at a slower rate, reaching adultlike levels (or maturity) well into middle childhood and adolescence (Freire et al., 2006; Hadad et al., 2011). This contrast in developmental milestones is likely related to the different visual processing skills that may contribute to the processing of more complex biological motion (Troje, 2008). Specifically, selective visual attention has been found to strongly contribute to the processing of biological motion (Cavanagh et al., 2001; Ji et al., 2020). However, given the dynamic nature of the biological motion stimuli, dynamic visual attention may also play an important role (Koldewyn et al., 2010; Koldewyn et al., 2013).

The study of biological motion processing offers a unique opportunity to investigate attention to dynamic stimuli that also has social developmental implications (Pavlova, 2012). Thus, the overarching aim of my dissertation was to examine the development of biological motion processing between childhood and early adolescence in two ways, a) looking at the role of dynamic attentional processing and b) at the link to real-world socially competent behaviour. In Manuscript 1 (Chapter III), the contribution of dynamic attention was examined by comparing the developmental relationship between biological motion processing and multiple object tracking. In Manuscript 2 (Chapter VI), the social perceptual component of biological motion processing was examined with an emphasis on the relationship between biological motion processing and real-world social behaviour, in terms of parent ratings of social competence. Together, the examination of the development of biological motion processing and the role of dynamic attention in the school age range will offer insight into the development of real-world social behaviour.

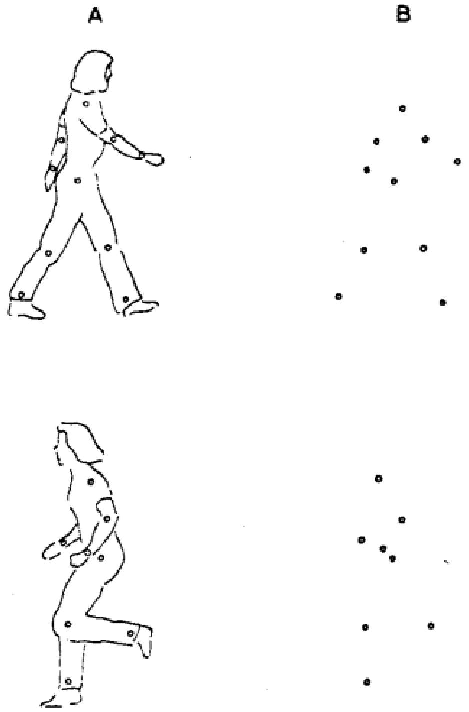
Chapter II: Literature Review

Measuring Biological Motion Processing

Johansson (1973) introduced the point-light display (PLD) technique for studying different types of human motion. He had been searching for an avenue to study body motion that captured the complex and ecologically relevant natural motion more than the standard mechanical motion that was being used at the time. To do so, he attached small lights to the major joints of human actors and filmed them performing specific actions or movements in a dark room. What remained was the dynamic representations of a walking human form composed of 10 white dots that represent the head, shoulders, hips, elbows, wrists, knees, and ankles on a black background (see Figure 1). Although this technique isolates motion from other sources of information, such as facial information, hair, clothing, and some morphology of the body (Troje, 2013), the proximal motion patterns presented were found to carry all the essential information needed for immediate visual identification of such human motion (Johansson, 1973). Thus, the visual processing of PLDs requires the tracking of points over time, where the points of light each have unique velocities and appear connected in a way that strongly suggests a coherent whole body, despite no visible body contour (Das et al., 2009; Neri et al., 1998; Viviani & Stucchi, 1992).

Figure 1

Point-Light Display of Biological Motion



Note. Outline contours of a walking and a running subject (A) and the corresponding dot configurations (B). Reprinted from "Visual Perception of Biological Motion and a Model for its Analysis" by Johansson, G., 1973, *Perception & Psychophysics, 14*(2), 201-211.

Johansson's (1973, 1975) PLD technique has since been used across many different experimental paradigms and perceptual tasks to assess biological motion processing. While the tasks vary considerably, they can generally be used to measure first-order, direct, or instrumental processing of biological motion (Federici et al., 2020). The most basic biological motion tasks (i.e., first order) simply require the detection of biological motion stimuli. Due to the simplicity of this version of the task, it has especially been used to measure infant looking preferences (Fox & McDaniel, 1982; Simion et al., 2008). The classic measurement of biological motion involves the *discrimination* between a human PLD and a scrambled collection of the dots, or an inanimate object (Troje, 2013). *Direction discrimination* tasks involve determining the direction that the PLD is walking. The walker can either be facing left or right, or facing each direction at an angle (i.e., subtended by several degrees). To increase the complexity of the biological motion tasks, a field of masking noise dots, typically composed of "scrambled" walkers in which each dot in the mask mimics the motion of a single walker dot, has been added to the tasks (Bertenthal & Pinto, 1994). By gradually increasing the density of the mask, researchers can determine an individual's sensitivity to perceiving the human motion (i.e., noise threshold). Tasks that involve identifying the action, emotion, or style of the PLD have been developed (Alaerts et al., 2011; Clarke et al., 2005) to tap into a more instrumental level of biological motion processing.

Development of Biological Motion Processing

While the biological motion task was initially used with adults, interest in how it develops early in life led to its use with both infants and children. Based on performance on the detection/discrimination tasks, the ability to identify the presence of biological motion appears to develop relatively quickly during infancy and the first two years of life (Kuhlmeier et al., 2010; Sifre et al., 2018), with adult-like accuracy by 5 years of age (Blake et al., 2003; Pavlova et al., 2001). However, biological motion discrimination appears to follow a longer developmental trajectory, continuing through childhood and adolescence, when attention must be allocated to more complex and ambiguous conditions (e.g., through a mask of noise dots). For example, Freire et al. (2006) found that when discriminating PLDs of human movements from scrambled versions without noise, 6-year-old, 9-year-old, and adult participants reached ceiling levels with no differences in accuracy among the age groups. However, when noise dots were gradually added to assess the participants' noise threshold value (i.e., number of noise dots that could be tolerated while still providing correct responses), performance improved linearly with age, as the

6-year-olds tolerated a significantly smaller number of noise dots than did the adults. In examining the developmental trajectory in children aged 5-12 years, Annaz et al. (2010) found a linear relationship between biological motion performance and age, indicating that this ability continues to improve into adolescence. In a developmental study of global and biological motion in children and adults aged 6-26 years, Hadad et al. (2011) found a quadratic trajectory in performance on a discrimination biological motion task presented in noise, with noise threshold improvements occurring between 7 and 10 years of age, and adult-like performance by 13 years of age. Improvements in performance with age have also been found using a variation of the direction discrimination task with a noise mask in a group of 7-12-year-olds (Rice et al., 2016), suggesting that performance on masked direction discrimination tasks may also improve with age.

The Essential Components of Biological Motion Processing

Local and global motion processing, social perception, and reflexive and effortful attention have been identified as essential components in the processing of biological motion. Together, these components work collaboratively to enhance the ability to recognize and interpret dynamic human movements to successfully perform the biological motion tasks (Thompson & Parasuraman, 2012).

Local and Global Motion Processing

The perception of the human form from biological motion is achieved by integrating the information from different motion cues, including both local and global motion cues. Local signals include information contained in the motion signals from individual dots (Mather et al., 1992). These individual dots represent acceleration and smooth deceleration movement of the individual body parts, such as arms, legs and head. The motion of the feet has been found to be particularly informative, especially in discriminating the direction of the motion (Chang & Troje, 2009). Global cues are predominantly derived from the displays' spatiotemporal organization which together creates a motion mediated global shape. This shape is characterized by the relationship between the points of the limbs that follow a functional pattern that is unique to humans (Cutting, 1981; Troje, 2013). While the utility and dominance of these cues for biological motion processing have been debated, the current consensus is that the relative contribution of the cue is thought to vary depending on the demands of the task (Hirai & Senju, 2020), such as the complexity of the movement and the level of noise in the visual scene (Troje & Chang, 2023). In one example, Troje (2008, 2013) suggests that global cues may be more implicated in biological motion detection and are more heavily impacted by masking noise, whereas local cues may be more implicated in direction discrimination. The two mechanisms may also fulfill complementary functions, in that the local motion guides attention to visual stimuli that are then scrutinized to derive further information from the motion-mediated global dynamic shape (Hirai & Senju, 2020; Troje & Chang, 2023). Ultimately, local and global visual motion cues converge to create a signal that is perceived to be social in nature.

Social Perception

Despite being measured with PLDs that are void of traditionally examined social information (e.g., face and eyes), the briefly presented stimuli are consistently perceived as socially relevant information (Thornton, 2013; Troje, 2013; Westhoff & Troje, 2007). For example, complex social information such as the individual's actions (e.g., Insch et al., 2012), emotions (e.g., Atkinson et al., 2004; Spencer et al., 2016), and even intentions (e.g., Hohmann et al., 2011; Manera et al., 2011) can be interpreted from these stimuli. The examination of neural correlates also provided evidence for the social perceptual component of biological motion. Specifically, neural underpinnings (e.g., superior temporal sulcus, STS; Duarte et al., 2022; Grossman & Blake, 2002; Krakowski et al., 2011; Pelphrey & Carter, 2008) used in the processing of biological motion overlap with brain regions involved in processing other basic social signals, such as facial expression and gaze directions (Engell & McCarthy, 2013; Kilford et al., 2016), and in the social brain network more generally (Puglia & Morris, 2017; Sokolov et al., 2018). Furthermore, the activity in brain regions that are central to the recognition of human actions, such as the STS, are modulated by the attentional demands of the biological motion task (e.g., Safford et al., 2010; Sokolov et al., 2018).

Reflexive and Effortful Attending

Visual attention is a cognitive process that helps orient and focus cognitive resources on relevant environmental information, while filtering out irrelevant distractions in the visual field (Amso & Scerif, 2015; Burack et al., 2017). In the context of biological motion processing, attention allows for the prioritization of specific aspects of the moving body which enable an accurate perception and interpretation of the social information (Toje, 2008). While there is a general agreement that the ability to attend is crucial for perceiving and interpreting biological motion (Thompson & Parasuraman, 2012), whether attention is allocated reflexively (i.e., without conscious control) or requires the effortful control of attention that is thus subject to capacity limitations is a source of debate.

Intrinsic and Reflexive. The primitive necessity of biological motion processing for survival in the natural environment and the ease with which the human form can be seen from the PLDs led Johansson (1973, 1975) and others (Giese & Poggio, 2003; Mather et al., 1992; Thornton & Vuong, 2004) to suggest that that some aspects of biological motion processing may occur automatically, without explicit attentional control. According to this view, the visual system may have specialized mechanisms that automatically detect and extract information from biological motion. Thus, the basic perception and detection of biological motion can occur rapidly and unconsciously via reflexive attention in a bottom-up direction without effortful attentional control (Wang et al., 2014). Evidence from infants, as young as a couple of days old, suggests that a sensitivity and preference for biological motion is largely intrinsic and independent from experience given that they have had relatively little socialization by this point in their life span (Bardi et al., 2014; Simion et al., 2008). Bardi et al. (2015) found that walking direction of a PLD (facing either left or right) triggered automatic orienting of visual-spatial attention in infants, such that saccade latencies (i.e., eye movement time) were significantly faster in congruent than incongruent trials for upright PLDs. Using a PLD walking in either direction as a central cue, Zhao et al. (2014) found that reflexive orienting of attention to biological walking direction was displayed as early as 4 years old. However, the overall reaction time was slower in the child group than the adult group. Among adults, Shi et al. (2010) demonstrated that PLD walking direction can induce a robust reflexive attentional orientation (e.g., automatically orient to the walking direction) using a central cueing task. Specifically, they found that the discrimination of the central target was slowed when it followed an incongruent walking cue, suggesting that attention was involuntarily oriented to the walking direction of the cue.

Effortful. While biological motion can be processed automatically, an attentional selection mechanism that is necessary under certain conditions (Cavanagh et al., 2001; Chandrasekaran et al., 2010) may contribute to the longer developmental trajectory. In conditions in which biological motion stimuli are ambiguous, degraded, or overlapping one another, as is commonly the case in the busy and complex natural environment, attentional resources appear to be needed for effective processing (Thompson & Parasuraman, 2012). Specifically, selective attention has been identified as a possible underlying mechanism for biological motion processing. For example, Cavanagh et al. (2001) demonstrated the role of selective attention when detecting biological motion walking direction in a visual search display. They found that to identify the target walking in the opposite direction of distractor walkers, each walker needed to be individually selected to determine their facing direction.

Another way in which the relationship between attention and biological motion has been examined is by measuring the relationship between the efficiency with which an individual controls attention and their ability to process biological motion. Finding such a correlation does not explicitly indicate the role that attention plays, but it does inform of the possible type of attention that may be implicated and warranting further direct investigation. Chandrasekaran et al. (2010) compared performance on a masked direction discrimination biological motion task with performance on measures of selective attention, including a visual search task, a Stroop task, and the Attention Network Test (ANT) that combines a Posner cueing paradigm with an Eriksen flanker task – measuring alerting, orienting, and executive control. They found a relationship between biological motion performance and selective attention, in that those who scored higher on tasks of attending also performed better in discriminating biological motion direction. This was true both when the motion was embedded in a mask of noise dots and when it appeared alone without any masking. In contrast, Agnew et al. (2020) did not find a relationship between biological motion performance and a similar set of selective attention tasks among young and older adults. They suggested that the facing direction discrimination task that they used may not have engaged active attentional processing that was central in Chandrasekaran et al. (2010)'s biological motion tasks.

Although the role of selective attention in biological motion processing has been demonstrated both directly and indirectly (e.g., Cavanagh et al., 2001; Chandrasekaran et al., 2010), the real-world implications have been limited by the common use of stimuli that are static, which is not typically the case for relevant social information in real-world environments (Birmingham & Kingstone, 2009; Liang et al., 2022). Accordingly, examining the relationship between biological motion processing and attention tasks that also involves the allocation of attention to stimuli that are in motion, such as the multiple object tracking task, may shed light on the visual attention that is implicated in processing dynamic scenes.

Dynamic Attention: When Stimuli are in Motion

Dynamic attention refers to keeping track of a target of interest and maintaining its continuity as it moves across space in a visual scene and across time (Cavanagh et al., 2014). Dynamic attention has been widely studied using the multiple object tracking (MOT) task (Pylyshyn & Storm, 1988), which involves simultaneously monitoring the paths of multiple concurrently moving objects among distractors (Pylyshyn, 2001). In the real-world, this skill is particularly important for attending to multiple sources of moving information, as is the case when monitoring vehicles and signs while driving or while monitoring the presence and location of opponents while playing team sports (Faubert & Sidebottom, 2012; Jin et al., 2020). Pylyshyn and Storm (1988) initially introduced the experimental MOT task to examine how the visual system allows for attentional focus to be simultaneously divided among several moving objects. The original version of this task required observers to track between one and five identical targets situated on a visual field with physically indistinguishable distractors, with a total of 10 independently moving items. During the period of tracking, a white square appeared around a single item and the observers were required to indicate if this object was a target by pressing a response button. The accuracy and speed of responses decreased with the increase in number of targets being tracked, with 4-5 targets being tracked by young adults with 85% accuracy. Subsequently, four items have been suggested as the consensus target limit in MOT (Suchow et al., 2014).

The traditional outcome measure for the MOT task was the accuracy rate for specific number of targets (Alvarez & Franconeri, 2007), but the speed threshold approach (i.e., the average target speed that participants successfully track) has also been used (Tullo et al., 2018). The advantages of this approach are that it is more sensitive to individual differences in task performance (Tullo et al., 2018) and also highlights the dynamic (motion) component of the task as well as the precision and efficiency with which attention can be allocated to objects in motion (Parsons, 2022). Three-dimensional versions of the task have also been developed to better reflect the depth and object interactions (i.e., occluding and colliding) that occur and likely impact dynamic attention in the real-world (e.g., Rehman et al., 2015; Romeas et al., 2016; Tullo, Guy et al., 2018). Decreases in accuracy based on task demands, such as an increased number of targets (Alvarez & Franconeri, 2007; Pylyshyn & Storm, 1998), increased trial duration (Oksama & Hyönä, 2004), increased speed of the items (Feria, 2013; Meyerhoff et al., 2016), and the addition of more distractors (Bettencourt & Somers, 2009) are thought to reflect not only the role of attention in MOT but also the limited capacity of attention resources in dynamic scenes (Huang et al., 2012; Tullo et al., 2018).

Developmental improvements in dynamic attention, as measured by MOT performance in 2D displays, have been found to occur in late childhood into adolescence, although significant improvements occur between 5 and 7 years of age, and adultlike levels of performance appear between the ages of 11 and 13 years (Trick et al., 2009). While developmental improvements in dynamic attention on 3D MOT displays have been examined to a much lesser extent, initial evidence suggests similar improvements with age until adultlike performance around 13 years of age (Brockhoff et al., 2016). Accordingly, the MOT task is thought to be sufficiently sensitive to act as a test of individual differences in dynamic visual attention (Meyerhoff & Papenmeier, 2020) that is also sensitive to developmental changes across childhood and adolescence.

Biological Motion Processing Model: Attentional Implication

Taking into consideration the contribution of global and local cues, social perception, and attention, Hirai and Senju (2020) proposed a two-stage processing model to describe the development of biological motion processing. They referred to the first process as the "Step Detector", which reflects the rapid, reflexive processing of the local motion primarily located in the feet. This system emerges early, is less dependent on experience, and may be evolutionarily driven to support survival through the detection of life (Troje & Chang, 2023; Troje & Westhoff, 2006; Wang et al., 2018). The second process, called the "Bodily Action Evaluator" (BAE), is involved in the interpretation of the global, configural, information, such as the direction, action or emotion of the walker. The BAE processing involves top-down, effortful control of attention and develops gradually through intensive visual experience, which becomes human action specific due to the frequency of exposure (Johnson, 2000). While the Step Detector plays the most significant role during the first few months of life, Hirai and Senju (2020) propose that it continues to facilitate the orienting of the BAE throughout development, especially for tasks like direction discrimination. Therefore, the added reflexive orienting support from the Step Detector may contribute to a unique and possibly accelerated developmental trajectory of attention to biological motion, compared to the development of attention to non-social motion.

Real-World Social Developmental Implications

The functional significance of the development of attention for biological motion lies in its necessity for efficiently detecting and interpreting the movements of others during social interactions to respond in a socially competent manner (Capozzi & Ristic, 2018; Neri et al., 2006; Sweeny et al., 2013; Yoon & Johnson, 2009). Social competence is generally considered as the ability to achieve goals effectively while maintaining positive relationships in social interactions (Rubin & Rose-Krasnor, 1992). Social competence is a dynamic construct that begins with early exchanges in the dyadic caregiver-infant relationship and extends into the social world of peers who become friends and romantic partners (Obradović, et al., 2006). It is thought to represent the interplay between social cognition and social skills, in that it is the ultimate outcome of social cognitive processes that allow for the perception and interpretation of the immense amount of social information from the environment and the social skills to effectively act on this information (Tuerk et al., 2021; Yager & Ehmann, 2006). These social cognitive processes include, but are not limited to, social perception (i.e., the prioritization and detection of social information), emotion recognition (i.e., accurately identifying the emotional state of others), and theory of mind (i.e., inferring the thoughts and intentions of other people) (Morrison et al., 2020).

The acquisition of socio-cognitive abilities and ultimately the development of social competence emerge because of a developmental cascade, in that basic skills encourage and allow for the refinement of more complex ones (Beaudoin & Beauchamp, 2020). For example, Soto-Icaza et al. (2015) proposed a framework for understanding the development of social cognition and ultimately social functioning, in which the perception of biological motion, that is the movement of the human body, is one of the first signs of social capacities. They described the perception of biological motion as a sensory device that allows for distinguishing among social agents. In their framework of the early temporal sequence of social development, perceiving biological motion is a precursor for the acquisition of further social abilities, such as face recognition and theory of mind (Soto-Icaza et al., 2015). In her seminal review paper on both typical and atypical social development, Pavlova (2012) proposed that body biological motion tasks may serve as a hallmark of social cognition and successful daily-life social functioning. The close connection between biological motion perception and social abilities suggests that the perceptual system for biological motion might be functionally integrated with social abilities. Pavlova (2012) further highlighted that the structural and functional brain connectivity for biological processing and visual social cognition are overlapping neural networks.

Measuring Social Competence

The multidimensional nature of social competence makes it challenging to define and assess for both research purposes as well as for social skills intervention (Junge et al., 2020). In a theoretical review, Rose-Krasnor (1997) proposed a *Social Competence Prism* framework that suggests that social competence can be studied empirically at two levels: the index level and the skills level. The index level is determined through transactions with others and tends to be context-dependent and represented by social success (e.g., friendships, prosocial behaviour, group status, peer acceptance) (Flannery & Smith, 2017), whereas the skills level is concerned with the foundational skills and motivations that are primarily within the individual (e.g., empathy, communication, emotion regulation, social problem solving, social encoding) (Junge et al., 2020). While measurements at the index level represent more general competence, developmental changes may be most apparent at the skills level (Rose-Krasnor, 1997). Thus, assessing the foundational skills level of social competence may be better suited when considering the relationship between social competence and biological motion processing in children and adolescents, as biological motion processing is also considered to be a foundational perceptual skill (Bonatti et al., 2002).

Based on the skills level of Rose-Krasnor's (1997) prism theory of social competence, Yager and Iarocci (2013) developed the Multidimensional Scale of Social Competence (MSCS) to reflect the multidimensional conceptualization of social competence. The caregiver and self-rating versions of the scale are used to measure social motivation, social inferencing, demonstrating empathic concern, social knowledge, verbal conversation skills, non-verbal sending skills, and emotion regulation. The scale was developed primarily to measure social competence in children on the autism spectrum who are highly verbal and have average intelligence. The social behaviours of these individuals are more likely to overlap with the variability seen in the neurotypical population, and therefore the scale is appropriate to use with the general population as well (Trevisan et al., 2018). Historically, most of the psychometric tools used to measure social competence when looking at the relationship with biological motion processing are questionnaires designed for measuring and quantifying social characteristics to screen for clinical diagnoses, such as autism spectrum disorder (ASD) (Annaz et al., 2010; Kou et al., 2019). While these measures typically do tap into the desired skill level, they also frequently include subscales to evaluate other diagnostic features (e.g., sensory sensitivity and repetitive interests/behaviour) which introduce construct irrelevant variance when used as a measure of social competence. The MSCS does not include such subscales making it more appropriate for use with both clinical and non-clinical populations, and a potentially useful tool for examining the relationship between the foundational skill level of social competence and biological motion processing.

Program of Research

The objectives of this dissertation were to (i) explore the contributions of dynamic visual attention by examining the developmental relationship between performance on the 3D biological motion task and on a 3D - MOT task and to (ii) examine the social perceptual component of biological motion processing by comparing biological motion performance to real-world social competence in the middle childhood to adolescent age range. We chose to examine the role of dynamic attention in performance on a 3D masked direction discrimination version of the biological motion task, as tasks with noise have been proposed to have a longer developmental period, and are thought to require attention to process. The increase in task complexity brought by the mask was also proposed to reflect the complexity of the real-world. The direction discrimination version was chosen in part because the act of walking is one of the most common biological motions observed in the real-world day to day lives. The middle childhood to adolescent age range was selected as evidence from studies using 2D biological motion tasks suggests that performance may continue to improve through childhood and into adolescence (Hadad et al., 2011). Furthermore, middle childhood to early adolescence is a time of immense social learning and cognitive development and during which social interactions also become more complex (Monahan & Steinberg, 2011).

Chapter III - Manuscript 1

Biological Motion and Multiple Object Tracking Performance Develop Similarly from Childhood through Early Adolescence

Emily Stubbert[1], Domenico Tullo[2], Jocelyn Faubert[3], Armando Bertone[1], Jacob A. Burack[1]

[1]Educational and Counselling Psychology, McGill University,

[2] School of Education, University of California Irvine,

[3] École d'Optométrie, Université de Montréal,

Author Note: This manuscript has been published online in *Cognitive Development*.

Stubbert, E., Tullo, D., Faubert, J., Bertone, A., & Burack, J.A. (2023). Biological motion and multiple object tracking performance develop similarly from childhood through early adolescence. *Cognitive Development, 67,* 101360. https://doi.org/10.1016/j.cogdev.2023.101360

Highlights

1. 3D biological motion and MOT task performance was measured in 6–14-year-olds
2. Biological motion and MOT task performance improved similarly across age
3. Commonalities in dynamic attention processes may have overridden qualitative task differences

Abstract

The multiple object tracking (MOT) (Pylyshyn & Storm, 1988) and biological motion (Johansson, 1973) tasks are both used to assess the perception of and attention to motion. These abilities are essential to the dynamic real-world task of identifying and monitoring multiple moving stimuli in the environment. We examined cross-sectionally the developmental changes in dynamic visual attention using 3D versions of both the MOT task and a masked direction discrimination biological motion task among 42 children and adolescents aged 6-14 years. The concurrent examination of these two tasks also allowed for an initial assessment of the pattern of task performance improvements with age. Performance on both tasks was found to improve with age and the relationship between the two tasks did not differ as a function of age, suggesting that biological motion and MOT attentional abilities improve similarly across age.

Keywords: biological motion, MOT, attention, social attention, development

Biological Motion and Multiple Object Tracking Performance Develop Similarly from Childhood through Early Adolescence

In the visual domain, attentional processes mediate the selection of relevant information in our surroundings - such as features and/or objects in certain locations - to guide our decision-making that ultimately defines our adaptive and conscious actions (Amso & Scerif, 2015). The theoretical framework within which attentional selection is discussed has evolved from a more traditional information-processing model, in which attention is seen as the *gatekeeper* between sensory information and action, to a more nuanced framework in which attention is *both the cause and the outcome* within a larger dynamic system with considerable interplay between the characteristics of the individual (i.e., life history, motivation) and the complex real-world environment (Burack et al., 2017; Ristic & Enns, 2015a; 2015b).

Capturing the complexity of the interactive relationship between attention and the real-world environment has proven to be challenging for experimental researchers (Birmingham et al., 2012). In the traditional approach, the development of attention was assessed with a singular static task in which a specific attentional component is isolated. This approach was based on the assumption of situational invariance, for which findings extrapolate to different individuals and situations. However, the shift in the framework would suggest that the way an individual may prioritize and efficiently attend to information varies based on many factors, such as the information's content or nature. According to this framework, one emphasis is on understanding how information that is socially relevant, such as humans, faces, and eyes, may be processed and attended to differently than non-socially relevant information. For example, understanding and attending to important socially-contingent visual information is thought to rely on a unique neurological network specific for social information (Blakemore, 2008; Grossmann & Johnson, 2007). This social brain network develops over time through *interactive specialization* that occurs through experience with social stimuli, as opposed to all information being processed in a specific area designated for attention more generally (Johnson et al., 2005). Accordingly, attention to social information, such as human faces, direction of gaze, movement, and emotions may develop differently than attention to non-social information (Birmingham & Kingstone, 2009; Liu et al., 2021). Therefore, the nature of the information being processed is an essential component to consider when assessing the development of attention within the dynamic system framework.

Two paradigms that have been used in the experimental literature for studying attention as a dynamic system with multiple interacting components are the (i) multiple object tracking (MOT) (Pylyshyn & Storm, 1988), and (ii) biological motion tasks (Johansson, 1973). Although both require attending to the confluence of movement in space, they are qualitatively different regarding their nature, with socially relevant information being presented in the biological motion task (i.e., human walker) and non-socially relevant information in the MOT task (i.e., spheres).

The MOT task was developed by Pylyshyn and Storm (1988) to assess the ability to simultaneously focus on and track multiple specific target objects as they move among distractor objects in a random manner. The original version of this task required observers to track between one and five identical targets situated on a visual field with identical distractors, with a total of 10 independently moving items. Following the period of tracking, a white square appeared around a single item and the observers were required to indicate if this object was a target by pressing a response button. Although the initial selection of the targets is considered to be pre-attentive, with a limited capacity of roughly four items in the visual field (Cowan, 2001), the task of tracking requires the allocation of considerable attentional effort (Pylyshyn, 1994; Pylyshyn & Storm, 1988). In addition, the selective, distributed, and sustained components of visual attention have all been identified as essential to successfully locating and tracking the position of multiple independent objects simultaneously over time (see Scholl, 2009 for review). Specifically, selective attention is required for focusing on a target object or multiple objects while ignoring distractor objects, distributed attention is required for spreading attentional resources across multiple objects while tracking moving objects in 2D or 3D space, and sustained attention for maintaining vigilance over a period of time both within and across trials (Pylyshyn & Storm, 1988; Scholl, 2009).

The role of attention in MOT has been explored by manipulating within-task factors that influence the allocation of attention, such as the number of targets to be tracked (Pylyshyn & Storm, 1988) and the speed of the objects (Alvarez & Franconeri, 2007; Meyerhoff et al., 2016). Performance on the MOT task has also been found to be impacted by individual differences in cognition (e.g., fluid reasoning intelligence; Tullo et al., 2018) and age (Trick et al., 2005). Improvements in tracking performance in 2D displays have been found from middle childhood into adolescence, with significant improvements occurring between 6 and 8 years of age and adultlike levels of performance appearing between the ages of 11 and 13 years (Trick et al., 2009; Trick et al., 2005). Similar developmental trajectories have been cited with 3D versions of the task, developed to reflect the depth and object interactions (i.e., occluding and colliding) that occur in the real world (e.g., Rehman et al., 2015; Romeas et al., 2016), with adultlike performance appearing around 13 years of age (Brockhoff et al., 2016). Taken together, the MOT task is a robust experimental task that offers a measurement of visual attention to dynamic non-social stimuli and is sensitive to developmental changes.

Biological motion refers to the movement of living organisms, including whole-body motion as well as the movement of individual body parts (i.e., hands, head, and arms). Attending to and interpreting these movements are thought to be fundamental aspects of effective social communication and interactions with other people, as they have the power to convey essential information such as mental states, personality, and emotions (Pavlova, 2012). Experimentally, biological motion is typically measured using a variation of Johansson's (1973) point-light walker technique which includes point-light displays (PLD). Point-light displays are dynamic representations of a human form composed of 10 to 15 white dots that represent the head, shoulders, hips, elbows, wrists, knees, and ankles on a black background. Despite the small number of moving points in the PLD, the motion patterns of a biological motion walker carry all the essential information needed for immediate identification of such human action (Johansson, 1973). The visual information from PLDs includes local motion signals derived from the individual dot motion as well as global form cues from the dynamic motion of the collection of dots (Kim et al., 2015; van Boxtel & Lu, 2015). Both local and global mechanisms contribute to the perception of biological motion and their relative contribution (i.e., the extent to which we rely more heavily on one over the other) may depend on the attentional demands of the task (Chang & Troje, 2009).

The attentional mechanisms through which biological motion is processed has been debated (Safford et al., 2010). The primitive necessity of this ability and the ease with which the human form can be seen from the PLDs led Johansson (1973, 1975) and others to emphasize the "spontaneous" and "automatic" nature of biological motion processing. In some cases, the features of biological motion are processed automatically without the explicit allocation of attentional resources (Bardi et al., 2014; Chandrasekaran et al., 2010; Mather et al., 1992; Shi et al., 2010; Thornton & Vuong, 2004; Yu et al., 2020). However, in conditions in which biological motion stimuli interact, are ambiguous, degraded, or overlapping with one another, as is commonly the case in busy and complex natural environments, attentional processes are required for effective task completion (Cavanagh et al., 2001; Ji et al., 2020; Thompson & Parasuraman, 2012). The complexity of the biological motion task has been increased by including a field of masking noise dots, in which each dot in the mask mimics the motion of a single walker dot. Although the walker can still be detected within the mask with above chance efficiency (Bertenthal & Pinto 1994), evidence that performance is significantly disrupted when a dual task is added (e.g., also monitoring rectangles throughout the task) suggests that the allocation of attention is required for accurately processing biological motion through a mask (Thornton et al., 2002). This indicates that perceiving biological motion is uniquely reflexive due to the social nature of the stimuli but requires effortful controlled processing under complex conditions, such as those in real-world social environments.

Under ideal conditions, the ability to simply detect the presence of biological motion appears to develop relatively quickly during infancy and the first two years of life (Kuhlmeier et al., 2010; Sifre et al., 2018), with adult-like accuracy by 5 years of age (Pavlova et al., 2001). However, when attention must be allocated to more complex and ambiguous conditions (e.g., through a mask of noise dots), discriminating the walking direction of biological motion appears to follow a longer developmental trajectory, continuing through childhood and adolescence (Friere et al., 2006). In a study of attention to biological motion in typically developing (TD) children aged 5-12 years and children with autism spectrum disorder (ASD), Annaz et al. (2010) found a linear relationship between biological motion performance and age in the TD group, indicating that this ability continues to improve into adolescence. In a developmental study of global and biological motion in TD children and adults, Hadad et al. (2011) found a quadratic relationship between biological motion and age, with improvements occurring between 7 and 10 years of age and adult-like performance by 13 years of age.

Evidence from the two studies of both biological motion and MOT tasks suggests attention plays a role in task performance on both, with a possible overlap in the attentional mechanisms (Legault & Faubert, 2012; Tyler & Grossman, 2011). In a study in which 3 groups of adults each completed one of a biological motion, coherent motion, or MOT task, Tyler and Grossman (2011) found that both biological motion and MOT can be processed using attentive mechanisms, but that the attention-limiting factors may differ between the two tasks, with biological motion being impacted by salience but MOT being impacted by task related factors (e.g., number of items being tracks or spatial proximity). Conversely, Legault and Faubert (2012) found improved performance on a masked biological motion task among older adults trained on 3D MOT, indicating some overlap in attentional and perceptual skills required for both tasks. Together, these findings suggest that attention is implicated in both the masked biological motion and MOT tasks, with some overlap in the attentional skills required to complete them. However, a greater emphasis on within-subjects effects, with participants concurrently completing both tasks, would provide a more nuanced examination of the relationship between these paradigms as well as of the individual differences factors predicting performance.

The concurrent examination of performance on the MOT and biological motion tasks allows for the exploration of the role of attention in biological motion perception and how this may be impacted by the nature of the motion of the stimuli to which attention is allocated. Both tasks involve the perception of and attention to motion, which is an essential part of the dynamic nature of the real-world environment. Although the trajectories of the local stimuli in the MOT and biological motion task differ, the efficient completion of both paradigms is contingent on actively updating the current position of multiple items among distractors in a dynamic field (e.g., Brodeur et al., 2013; Fougnie & Marois, 2006; Tombu & Seiffert, 2008). In the MOT task, the target spheres move linearly in random directions among distractor spheres. In contrast, the target dots in biological motion task move in non-linear manners which, in whole or in part, mimic the natural motion of a walking human. The dots in the mask act as distractors as they follow similar trajectories as the dots in the walker, but their spatial location is random. Thus, attention must be briefly sustained to the visual field and the location of the stimuli updated over time in both tasks, although the selection of the target dots among distractors in the biological motion task appears to be facilitated by the familiar social pattern of the motion.

The aim of the present study was to examine cross-sectionally the developmental changes in dynamic visual attention using 3D versions of the MOT task and a masked direction discrimination biological motion task among children and adolescents between the chronological ages of 6-14 years. This age range was selected as evidence from studies using 2D biological motion tasks suggests that performance may continue to improve through childhood and into adolescence (Hadad et al., 2011). As cognitive status is related to attention and has been found to impact MOT task performance (e.g., Tullo et al., 2018), we also took into account cognitive status (IQ) and performance on a separate, clinically validated measure of attention (CPT-3/KCPT-2). First, consistent with evidence of developmental improvements on these tasks (e.g., Annaz et al., 2010; Brockhoff et al., 2016), we hypothesized that performance would improve with age for both tasks. Second, as this was intended as an initial concurrent comparison of the developmental trajectories of performance on the MOT and biological motion tasks, we also explored whether the improvements differed as a function of age, possibly due to the reflexive processing of socially relevant information that is unique to the biological motion task (e.g., Liu et al., 2021), and not found in the MOT task.

Method

Participants

Forty-nine children and adolescents (24 males), ranging from 6-14 years old (*M* = 10y;1m, *SD* = 0y;2m), participated in the study. The group was spread relatively evenly across the age range, with twelve 6-7 year olds, twelve 8-9 year olds, thirteen 10-11 year olds, and twelve 12-14 year olds. Twenty percent of the sample (*n* =10) reported a household income below $50,000, 20.4% (*n* = 10) reported a household income of $50-79,999, 16.3% (*n* = 8) reported a household income of $80-109,000, 20.4% (*n* =10) reported a household income of $110-140,000, and 22.4% (*n* = 11) reported a household income above $140,000. With regard to cultural and ethnic backgrounds, 60% of the participants reported Canadian (*n* = 20), Canadian\Chinese (*n* = 5), Canadian\Pakistani (*n* = 2), Canadian\Pakistani\Salvadoran (*n* = 1), Canadian\Haitian (*n* = 1), or Canadian\Peruvian (*n* =1), 6% reported Italian (*n* = 3), 6% reported Middle Eastern (*n* = 3), 6% reported Armenian (*n* = 2), or Armenian\Hungarian (*n* = 1), 4 % reported Moroccan (*n* = 2), 4% reported Austrian\Salvadoran (n=2), 2% Indian (*n* = 1), 2% American (*n* = 1), 2% Metis (*n* = 1), 2% Israeli (*n* = 1), 2% Lebanese (*n* = 1), and 2% Persian (*n* = 1). None of the participants had any history of psychiatric or severe learning problems and all had IQs of 80 and above. All of the participants reported normal or corrected-to-normal vision. The experimental protocol was approved by the McGill University Research Ethics Board Office. The participants were recruited from the Montreal community via online classifieds.

Baseline Measures

Demographics Questionnaire

Caregivers completed a general background questionnaire to collect demographic information as well as information regarding the participants' gender, vision, medical, and educational history.

Cognitive Measure

The cognitive profile was obtained for each participant using the Wechsler Abbreviated Scale of Intelligence – Second edition (WASI-II; Wechsler, 2011). The WASI-II is a clinical cognitive test that is standardized for individuals 6-89 years old. The test is comprised of four subtests (i.e., Vocabulary, Similarities, Block Design, and Matrix Reasoning), whose scores yield a composite Perceptual Reasoning Index score (nonverbal IQ), a Verbal Comprehension Index score (verbal IQ), and a Full-Scale IQ score. The composites allowed for the determination of whether the TD participants meet the inclusion criteria (i.e., IQ >= 80).

Attention Measure

The participants completed either the Conners' Kiddie Continuous Performance Test (KCPT-2; Conners, 2015) or the Conners' Continuous Performance Test (CPT-3; Conners, 2014), which are clinically validated computer-based assessments of attention. The KCPT-2 is designed to be appropriate for children aged 4-7 years, and the CPT-3 is intended for children aged 8 years and older. The CPT-3 requires participants to press the space bar every time a letter appears, except for the letter "X". The time intervals between which the letters appear on the screen varies throughout the task. The task is 14 minutes long and is preceded by a short practice set (70 seconds) to make sure that the participants understand the instructions prior to commencing the test. The KCPT-2 follows a similar procedure except that the duration is shorter (i.e., 7 minutes) and the participants press the space bar every time an object appears, except for when the object is a ball. The CPT-3 and KCPT-2 tasks provide standardized attention data, based on age and gender-specific norms, for different facets of attention, including inattentiveness, impulsivity, sustained attention, and vigilance. Higher t-scores indicate greater difficulties with attention, with the average t-score falling between 40 and 59, and t-scores of 60 and above indicating atypical attention. The CPT-3 / KCPT-2 distractibility (d') t-score was used as a measure of general attention in the current study and will be referred to as "CPT" moving forward.

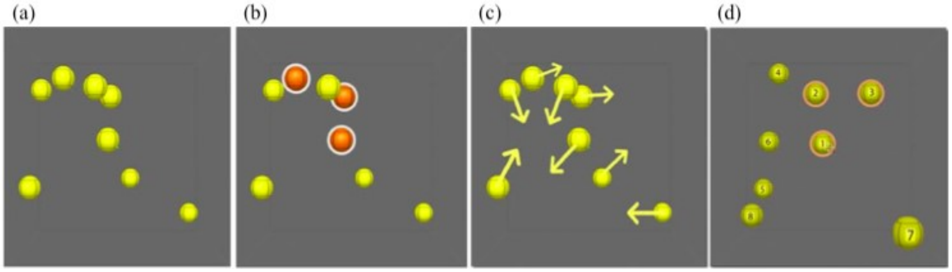
Experimental Tasks

Three-Dimensional Multiple Object Tracking (MOT) task

The participants were presented with 8 spheres moving in a virtual volumetric space in different directions and were asked to track 3 spheres during each trial (Figure 2). The spheres moved in a virtual cube with transparent virtual walls subtending 45 degrees when viewed from 100cm. Each trial started with the presentation of the spheres located randomly in the 3D space (Figure 2a.). Three of the 8 spheres then changed from yellow to orange, denoting those that must be attentively tracked for that trial (Figure 2b). The spheres then returned back to their original colour (yellow) and were set in motion for 8 seconds, during which they were to be tracked by the participant (Figure 2c). When the spheres stopped, the participant was asked to identify which of the spheres (now numbered) were tracked (either verbally or with a keypad), and those spheres were subsequently highlighted (Figure 2d). If the participant correctly tracked the spheres for that trial, the speed increased. Conversely, the speed decreased if the responses were incorrect. Initial speed was set at 68 centimeters per second (cm/s), with possible speeds ranging from 0.06 cm/s to 544 cm/s. The speed of each trial was controlled using a 1-up 1-down staircase procedure (Levitt, 2005), with the speed threshold score obtained after six inversions (Legault et al., 2012). Thus, performance was defined as the maximum speed at which participants could correctly track 3 out of 8 spheres (i.e., speed threshold). Before the experimental trials, the participants completed up to six practice trials, during which they were asked to track one of eight spheres. Participants completed two rounds of the main task and the average of the two speed thresholds was used as their overall score.

Figure 1

Procedural Representation of the 3-Dimensional MOT Task



Note. a) The 8 spheres are presented in the visual field; b) the 3 target spheres are highlighted and participants are told to track these items; c) the spheres move randomly throughout the visual field for 8 seconds; d) numbers appear on all 8 spheres and the participant identify the 3 target spheres.

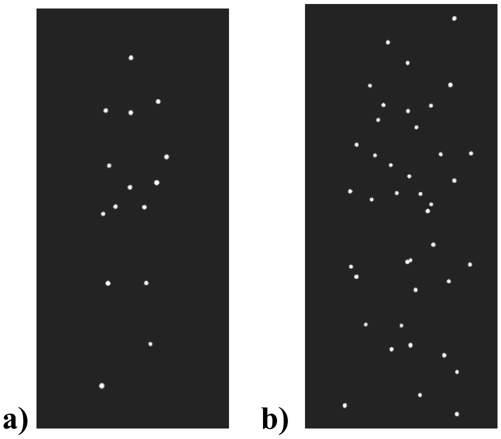
Three-Dimensional Biological Motion Task

The target stimuli for the 3D biological motion task were point-light walkers (Figure 1a). The point-light walker was presented upright and appeared to be walking on the spot in either the left or the right direction (-16 and 16 degrees) relative to the observer, subtending 45 degrees when viewed from 100 cm. The participants were asked to indicate whether the walker was going to the left or right by pressing the corresponding left or right button on a keypad. The duration of each trial animation was one second followed by a blank screen delay, with the next trial only beginning once the participant had responded. The strength or saliency of the point-light walker was manipulated by adjusting the number of interfering noise dots (Figure 1b) presented simultaneously with the walker. The noise dots were randomly distributed within the array and the motion of the individual dots resembled the local movement of the individual dots comprising the intact walker. Accordingly, the walker and noise could be separated only by integrating the walker's biological motion, and not by differences in the individual dot elements (Legault et al., 2012); the size and appearance of all dots (noise and walker) were identical.

The task began without any noise, with the number of interfering dots increasing after correct responses, and vice versa. A noise threshold was determined using a 2-up 1-down staircase procedure, ending when 6 inversions had taken place (i.e., 2 correct answers followed by an incorrect answer). The threshold is the average of the number of noise dots present at each inversion. As such, performance is defined as the maximum number of noise dots through which the participants can accurately discriminate the direction of the point-light walker (i.e., noise threshold). The participants completed 10 practice trials of increasing difficulty (i.e., 2 trials at each noise level: 0, 25, 50, 75, and 100 dots) followed by three rounds of the main task. Three threshold scores were obtained from each participant, with the two most similar thresholds averaged and used in the analyses.

Figure 2

Example of Stimuli for the 3-Dimensional Biological Motion Task



Note. a) point-light walker in the left direction with no interfering dots present; b) point-light walker (left direction) presented with 25 interfering noise dots.

Procedure

The 3D biological motion and MOT tasks were controlled by a laptop and presented on a 50-inch 3D compatible HDTV. The participants wore 3D Active glasses and were seated one meter from the HDTV. Participants or research assistants inputted responses on a numeric keypad, which is a standalone device that consists of a grid of numbers, mathematical symbols, and additional function keys. The numeric keypad contained the numbers 0 to 9, along with mathematical operators like addition (+), subtraction (-), multiplication (*), division (/), and a decimal point (.), and keys for functions such as Enter, Clear, and Backspace. For the MOT task, the numbers 1-8 on the keypad were used. For the biological motion task, the "Num Lock" was engaged, and the 4 and 6 keys functioned as arrow keys that allowed the participant to indicate left (4) or right (8). Ethical consent was obtained from a parent or primary caregiver, and the researchers also obtained written or verbal assent from each participant depending on whether the child could write their name. The parents or primary caregivers also completed a demographics form. The testing took place over a 1.5-hour session, beginning with the measure of cognitive functioning (WASI-II) and establishing the baseline attention (Conners CPT). The participants then completed the two experimental tasks (3D MOT and 3D biological motion), with the order being counter-balanced across the participants. Since performance on the 3D tasks involves an adaptive staircase procedure (efficient testing technique that minimizes the number of trials to reach threshold performance), the time of administration varied across participants, but did not exceed 30 minutes. The 1.5 hour session included several short breaks between tasks and rounds that varied in length and frequency depending on the participant. The participants received compensation of $25 cash for their participation.

Results

Prior to the analyses, we excluded participants who violated two cases of Mahalanobis, Cooks d, or leverage, using critical values computed from the variables in the multiple regression analysis. Furthermore, violations of difference in fit and difference in betas also determined whether participants were removed from final multiple regression model using critical values computed from the primary regression analysis. As such, 7 participants' datasets were excluded from the final analysis. The final group included ten 6–7-year-olds, eleven 8–9-year-olds, thirteen 10–11-year-olds, and eight 12–14-year-olds (see Table 1 for means and standard deviations). The characteristics on cognitive (FSIQ) and attentional measures (Conners CPT) are presented in Table 2. The means and standard deviations for IQ and attentional measures were close to population parameters. Furthermore, preliminary analyses revealed no gender differences in age, FSIQ, Conners CPT, BM noise threshold, nor MOT speed threshold (see Table 2).

Table 1

Age Distribution of Final Group

Age Bracket	***n***	***M***	***SD***
6-7 years	10	7;0	0;6
8-9 years	11	9;0	0;8
10-11 years	13	10;11	0;8
12-14 years	8	13;6	0;11

Note. M = mean in years;months; SD = standard deviation in years;months.

Table 2

Participants' Characteristics by Gender

		Gender			
Variables	**Observations**	**Males**	**Females**	**Total**	**Test Statistic**
		n = 21	n = 21	N = 42	
Age	42	10;0(2;0)	10;0(2;9)	10;0(2;4)	$p = 0.835$
FSIQ	42	107.24(14.67)	106.33(12.73)	106.79(13.57)	$p = 0.832$
Conners CPT	42	47.67(6.95)	47.95(9.39)	47.81(8.16)	$p = 0.957$
BM noise threshold	42	54.52(57.07)	63.81(73.38)	59.17(65.10)	$p = 0.650$
MOT speed threshold	42	65.26(29.24)	65.65(29.82)	65.40(29.17)	$p = 0.911$

Note. Means and (standard deviations) presented. Age in years;months. Gender differences were analyzed by separate one-way between subjects ANOVAs. Wechsler Abbreviated Scale of Intelligence – 2nd Edition T-scores: Full-Scale IQ (FSIQ), Conners Continuous Performance Task – 3rd Edition or Kiddie Continuous Performance Test -2nd Edition detectability T-score (Conners CPT), biological motion (BM) noise threshold, MOT speed threshold in centimeters per second (cm/s).

Bivariate Pearson's correlations revealed both MOT ($r(40) = .67, p < .001$) and biological motion performance ($r(40) = .39, p = .009$) positively correlated with age, indicating significant improvements with age as predicted. A simple linear regression was conducted to examine the relationship between MOT performance and biological motion performance (Table 3). The results demonstrated a statistically significant model: $F(1, 40) = 10.54$, $p = .002$, $R^2 = 0.21$, Adjusted $R^2 = 0.19$; with biological motion performance predicting MOT performance: $b = 0.003$, $t(40) = 3.25$, $p = .002$.

In order to explore whether task performance followed a similar pattern of improvements across age, we conducted a multiple regression analysis with age, biological motion, and the interaction between age and biological motion as predictors of MOT (Table 3). To account for individual differences in the recruited sample, we also controlled for the effects of IQ and performance on a separate, clinically validated measure of attention: FSIQ and Conners CPT were entered as covariates. The final model was statistically significant: $F(5, 36) = 15.15$, $p < .001$, $R^2 = 0.68$, Adjusted $R^2 = 0.63$; although biological motion did not predict MOT while controlling for age, FSIQ, and clinically validated measure of attention: $b = -0.002$, $t(36) = -0.446$, $p = 0.659$. Moreover, no interaction was found between biological motion and age: $b = 0$, $t(36) = 0.694$, $p = 0.492$, indicating that the relationship between MOT and biological motion did not differ as a function of age while controlling for IQ and general measure of attention. The relationship between the task performance by age, Conners CPT, and FSIQ are presented in figures 3a and 3b.

Table 3

Multiple regression examining the relationship between MOT and BM, and the interactive effect of age.

Biological Motion: $R^2 = .21$, Adjusted $R^2 = .19$

Predictor	***b***	**SE (b)**	***B***	**Pearson R**	**sr^2**	***p***
Constant	0.78	.08				$p < .001$
BM	0.003	.001	0.46	.46	.21	$p = .002$

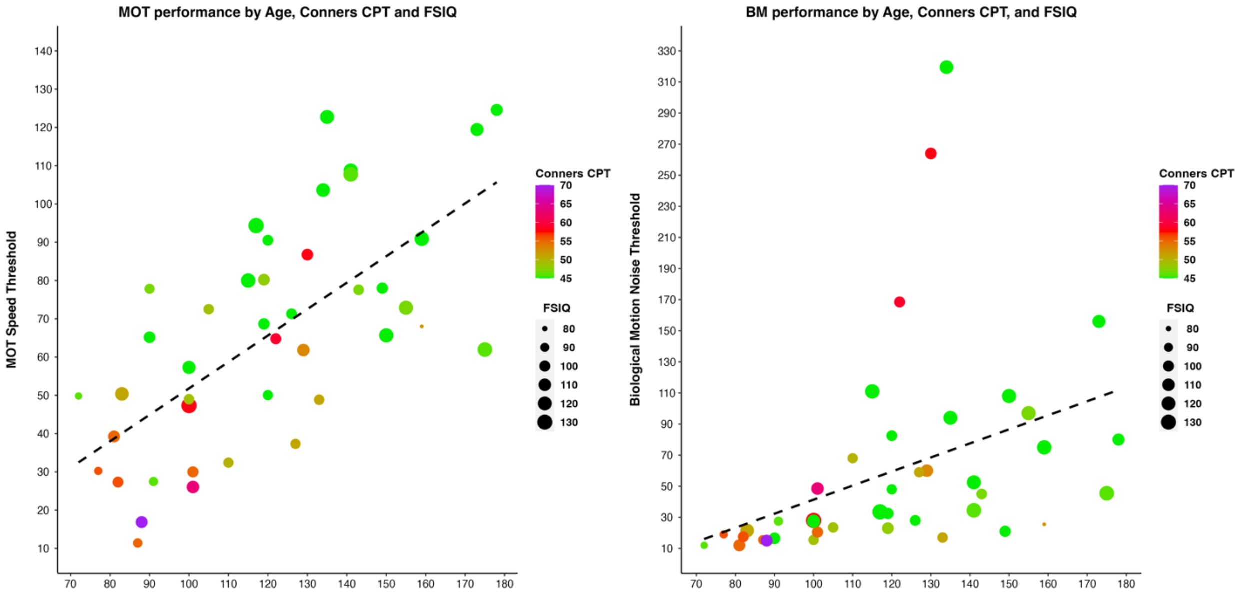
Age Interaction: $R^2 = .68$, Adjusted $R^2 = .63$

Predictors	***b***	**SE (b)**	***B***	**Pearson R**	**sr^2**	***p***
Constant	0.92	.55				$p = .105$
BM	-0.002	.005	-0.36	.46	0	$p = .375$
Age	0.004	.002	0.28	.67	.03	$p = .093$
FSIQ	0.005	.003	0.15	.45	.02	$p = .148$
Conners CPT	-0.02	.006	-0.42	-.65	.14	$p < .001$
Age X BM	0	0	0.60	.52	0	$p = .492$

Note. b and B represent the non-standardized and standardized coefficients, respectively. sr^2 denotes the squared semi-partial correlation.

Figure 3

Scatterplots Depicting Relationship Between Task Performance by Age, Conners CPT, and FSIQ



a) b)

Discussion

The goal of the current study was to explore the developmental changes in attention to dynamic non-social and social information in a cross-sectional sample of children and adolescents aged 6 to 14 years using 3D versions of the MOT task and a masked biological motion task. The first hypothesis was supported, with evidence that performance on both tasks was positively correlated with age. This is consistent with the findings of improved performance with age on varying versions of the 2D MOT and 2D biological motion tasks (e.g., Annaz et al., 2010; Brockhoff et al., 2016; Hadad et al., 2011; Trick et al., 2009). This finding extends the developmental literature to include the 3D versions of the tasks, which provide additional depth and object interactions (i.e., occluding and colliding) that occur in real-world environments. Furthermore, the evidence for developmental improvements in biological motion performance continues to support the notion that, despite the very early emergence of a reflexive sensitivity to perceiving biological motion among infants (Bardi et al., 2014; Simion et al., 2011), young children are less skilled than adolescents in attending to and processing biological motion through noise. Thus, our findings are consistent with evidence of a longer developmental trajectory that continues into adolescence when the biological motion task includes a mask of noise dots (Annaz et al., 2010; Freire et al., 2006; Hadad et al., 2011).

The relationship between the two tasks was also compared in order to explore whether the improvements differed as a function of age, possibly due to the automatic processing of socially relevant information that is unique to the biological motion task and not found in the MOT task. The findings from the exploratory multiple regression analysis revealed that the relationship between the 3D MOT and biological motion tasks did not differ as a function of age, suggesting that performance on the two tasks improved at a similar rate across age. We found the similar improvements even though the MOT and biological motion tasks are different types of tasks, in terms of both their nature (e.g., direction discrimination and tracking) and the information (e.g., non-social spheres, social walkers) to which attention is being directed. One possible explanation for why we found similar trajectories is that both dynamic tasks require similar visual attention processes. Accordingly, the commonality in dynamic attention processes may have overridden the qualitative differences between the two tasks. This is consistent with observed transfer of skill improvement from training on the MOT task to the biological motion task performance demonstrated in older adults (Legault & Faubert, 2012) that was attributed to the overlap in attentional and perceptual skills between the two tasks.

We had considered the possibility that the nature of the motion would differentially impact the allocation of attention to the tasks. Specifically, we thought that the socially relevant information available from the walker in the biological motion task could act as a catalyst for improving performance across ages. This is consistent with the notion that increased experience with socially relevant stimuli, such as the biological motion of others in the environment, ultimately fuels the growth and connections in the social brain network, making perception and attention for social information more efficient over time (Johnson et al., 2005). The increased experience makes the motion in the biological motion task inherently familiar, in addition to being systematic and thus predictable. In contrast, the motion in the MOT task is non-social and inherently random as the spheres bounce around the frame. In our study, this social disparity between the tasks did not lead to any differences in the developmental trajectories of task performance. Thus, one focus of future research should be the extent to which social information drives attentional performance across different ages, with regard to biological motion as well as to attention more generally.

Our findings highlight that performance on the 3D versions of both the MOT and biological motion tasks are associated with age-related improvements until around early adolescence, the age range at which performance seems to be adult-like on the 2D versions of these tasks (Annaz et al., 2010; Trick et al., 2009; Trick et al., 2005). However, in future studies, researchers need to consider Hadad et al.'s (2011) finding that improved performance on a biological motion task reflected a quadratic trend as a plateau was observed to begin around age 13 years continued until 25 years of age.

Conclusion

In sum, the findings presented here highlight that the visual attention skills required for perceiving the movements of others (i.e., biological motion) and tracking objects of interest (i.e., MOT) continue to develop through childhood into adolescence. They also provide preliminary evidence that biological motion and MOT attentional abilities improve similarly across age, suggesting concordant dynamic attention developmental trajectories despite being qualitatively different tasks.

Acknowledgments

This work was supported by the Social Science and Humanities Research Council Insight grant of Canada (grant number 435-2017-1422) awarded to J.A.B. and A.B.. Additionally, this work was supported by the Fonds de recherche du Quebec - Société et Culture (FRQSC) doctoral fellowship awarded to E.S. (grant number 268636), and the Canadian Institutes of Health Research postdoctoral fellowship (grant number 176576) and the Fonds de recherche du Québec – Santé (FRQS) postdoctoral fellowship (grant number 305855) awarded to D.T. We thank the children and their parents for participating in this study as well as the experimenters, Margarita Miseros, Olivia Furholter, Jordyne Shatzky-Greenspoon, Yara Maalouf, Julia Aboud, Myriam Lesage, and Mariam Ali, who helped in data collection. We also thank Vadim Sutyushev for his assistance with programing the experimental tasks.

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Chapter V: Bridging the Manuscripts

The focus of Manuscript 1 was the role of attention in the development of biological motion performance between middle childhood and adolescence. The developmental changes in dynamic visual attention using 3D versions of the MOT task and a masked direction discrimination biological motion task were examined cross-sectionally among children and adolescents between the chronological ages of 6-14 years. By concurrently measuring performance on both the 3D-MOT and biological motion task, we were able to examine the role that individual factors play in the processing of biological motion across this age range. Biological motion performance on the 3D mask direction discrimination task was found to be correlated with age, indicating that biological motion performance continues to improve with age through middle childhood and into adolescence. Performance on the MOT task was also significantly related to biological motion performance, suggesting a possible overlapping dynamic attention mechanism. In addition, the relationship between performance on the two tasks did not differ as a function of age, suggesting that they follow similar improvements with age. The findings from this study add to the literature suggesting that biological motion processing continues to improve into adolescences when the task is more complex (e.g., when it includes a mask of noise dots), compared to adult like performance by age 5 years in less complex tasks (e.g., when simply identifying or discriminating). Furthermore, the results also add to the literature suggesting that attention is implicated in biological motion task performance and points to dynamic attention as a possible key contributor.

The similar improvement in performance with age on the 3D biological motion and MOT tasks found in Manuscript 1 suggests that the early emerging reflexive attention to social information did not differentially impact the later development of the 3D masked direction discrimination biological motion task performance above and beyond that of the development of the non-social dynamic visual attention task (i.e., MOT) performance. Thus, in the second manuscript the social perceptual component of the 3D masked direction discrimination version of the biological motion task was examined. The focus was on the extent to which the performance on the biological motion task was related to real-world social behaviour in middle childhood and adolescence, as measured by parent ratings on the multidimensional scale of social competence questionnaire (MSCS; Yager & Iarocci, 2013). The MSCS was selected as it measures social competence at the finer-grained skill level, which may be more fitting when considering the relationship between social competence and biological motion processing, as biological motion processing is also considered to be a foundational visual perceptual skill (Bonatti et al., 2002). Implications for understanding the relationship between biological motion performance and the development of socially competent behaviour are discussed.

Chapter VI: Manuscript 2

Biological Motion Processing Does Not Predict Parent-Reported Social Competence Among Children and Early Adolescents

Emily Stubbert[1], Karen G. Arias[1], Domenico Tullo[2], Jocelyn Faubert[3], Armando Bertone[1], & Jacob A. Burack[1]

[1]Educational and Counselling Psychology, McGill University; [2]School of Education, University of California Irvine, [3]École d'Optométrie, Université de Montreal

Correspondence to Emily Stubbert, McGill University, Educational and Counselling Psychology, 3700 McTavish Street, Montreal, Canada, H3A 1Y2. Email: emily.stubbert@mail.mcgill.ca

Tel: 514-398-4242, Fax: 514-398-6968

The authors have no conflicts of interest to disclose.

Abstract

Our ability to efficiently detect and interpret biological motion information, such as that depicted by point-light walkers, is foundational for the development of adaptive social cognition and behaviour. In the present study, we assessed the relationship between biological motion processing and social competence in 45 children and adolescents (21 males) aged 6 through 14 years. We compared the participants' performance on a three-dimensional (3D) masked direction discrimination task with parent ratings on the Multidimensional Social Competence Scale (MSCS). Contrary to our hypothesis, the regression analysis demonstrated that biological motion performance did not predict social competence. Accordingly, while biological motion may be considered a hallmark of social cognition, the relationship between task performance and scores on measures of real-world socially competent behaviour appears to be more nuanced.

Keywords: Biological motion, social competence, social cognition, school aged children

Public Significance Statement:

The ability to discern movement patterns, such as distinguishing a person walking from a few moving dots, is believed to influence our social interactions. However, in this study we did not find a correlation between children and adolescents' ability to recognize these patterns and their social competence. This indicates that caution is needed when extracting social implications from experimental studies of the processing of people in motion.

Biological Motion Processing Does Not Predict Parent-Reported Social Competence Among Children and Early Adolescents

Our ability to behave adaptively within our environment depends to a great extent on efficient perception of and attention to social information, allowing us to interpret non-verbal cues during one-on-one interactions or navigating through a busy environment. The movement of living organisms, including whole-body motion as well as the movement of individual body parts (i.e., hands, head, and arms), is referred to as biological motion. Experimentally, biological motion processing is typically measured using some variation of Johansson's (1973) point-light displays (PLD), the dynamic representations of a human form composed of 10 to 15 white dots that represent the head, shoulders, hips, elbows, wrists, knees, and ankles on a black background. Despite the small number of moving points in these displays, the motion patterns of a biological motion PLD carries all the essential social information needed for the immediate identification of human motion (Blake & Shiffrar, 2007; Johansson, 1973; Thompson & Parasuraman, 2012).

Attending to and interpreting biological motion is argued to be an underlying cognitive operation integral to the effective social communication and interaction with others, and considered an essential aspect of social cognition (Pavlova, 2012), a specialized domain of cognition responsible for socially adaptive behaviour (Yager & Ehmann, 2006). Soto-Icaza et al. (2015) proposed a framework for understanding the development of social cognition and ultimately social functioning, in which the perception of biological motion is foundational. They described the perception of biological motion as a sensory device that allows for distinguishing between social agents, and as a precursor for the acquisition of further social abilities, such as face recognition and theory of mind. Within a developmental context, the perception and attention to biological motion becomes more complex and specific as infants age into childhood, progressing from the simple detection of the presence of motion to discriminating between biological motion and other motion types, ultimately leading to the capability to infer intentions from biological motion (Soto-Icaza et al., 2015). For example, whereas the ability to simply identify biological motion is relatively adultlike by 5 years of age (Pavlova et al., 2001), the ability to attend to and interpret biological motion information improves well into the school-age years and adolescence (Freire et al., 2006; Hadad et al., 2011). Some types of complex social information, such as those depicting an individual's actions (e.g., Hsiung et al., 2019; Insch et al., 2012; Sotoodeh et al., 2019), emotions (e.g., Atkinson et al., 2004; Lee & Kim, 2017; Mazzoni et al., 2020; Spencer et al., 2016) and even intentions (e.g., Manera et al., 2011), have been found to be detected and interpreted through simply biological motion by adulthood.

Biological motion tasks based on PLDs are considered to be social perception tasks and are good indicators of social cognition (Happé et al., 2017; Pavlova, 2012). While the theoretical importance of attending to and interpreting biological motion for the development of socially relevant skills has been demonstrated, its relationship to real-world socially competent behaviour remains unclear. Of the studies assessing biological motion processing in clinical populations (e.g., Jaywant et al., 2016; Okruszek & Pilecka, 2017; Reiss et al., 2005; Todorova et al., 2019; Williamson et al., 2015), those focused on its predictive value with regards to for social competence have for the most part been conducted with clinical populations for which atypical social functioning is a primary diagnostic marker, as is the case with autistic individuals (e.g., Blake et al., 2003; Koldewyn et al., 2010). In these studies, social behaviour is typically measured using autism-specific diagnostic tools, such as the Autism-Spectrum Quotient (AQ; Baron-Cohen et al., 2001), the Conners Autism Rating Scale (CARS; Schopler et al., 1986), the Social Communication Questionnaire (SCQ; Rutter et al., 2003), and the Social Responsiveness

Scale (SRS-2, Constantino & Gruber, 2012). The findings typically suggest variability in the relationship between biological motion processing and social competence during middle childhood to adolescence (i.e., 5-14 years). Initial evidence of an inverse relationship between biological motion performance and autism severity (Blake et al., 2003) has not been supported in subsequent studies (Alkire et al., 2020; Annaz et al., 2010; Cleary et al., 2014; Kou et al., 2019). In adults, the relationship between autism trait severity and biological motion performance has been found to vary depending on the biological motion task, with higher level tasks (e.g., interpersonal interaction) correlating with autism severity but lower-level action discrimination task did not (van Boxtel et al., 2017). To address this void, we aimed to assess the relationship between biological motion processing and real-life social competence in neurotypical school-aged children.

The evidence from the two studies on the relationship between performance on biological motion tasks and real-world social competence in neurotypical participants suggests that this relationship is dependent on the nature of the task and age group assessed. In their study of children aged 3-6 years, Zhai et al. (2020) examined interactive biological motion using two point-light agents. The participants were asked to determine whether the two point-light walker characters were interacting or not, and this task performance was assessed in relation to measures of social development defined by the teacher ratings on the Children's Social Competence Scale (CSCS; Li & Jiang, 2008; Zhang, 2002) as well as by language ability (Chinese PPVT-R). Across all ages, performance on the interactive biological motion task was found to continue to develop during the preschool years and, along with language ability, predicted social competence. However, when the participants were subdivided into age groups, biological motion performance predicted social competence only for the older 5–6-year-old participants. Zhai et al.

(2020) concluded that the perception of social interactions among preschool children becomes increasingly more important with age.

Using a noise masked paradigm, Miller and Saygin (2013) assessed the sensitivity of adults aged 18-31 years to biological motion when using either the form (indicate the facing direction) or motion cues (indicate the walking direction) of a PLD stimulus. The participants also completed a battery of social questionnaires, including the Empathy Quotient (EQ; Baron-Cohen & Wheelwright, 2004), Autism Quotient (AQ; Baron-Cohen et al., 2001) and Reading the Mind in the Eyes Test (RMET; Baron-Cohen et al., 2001). Individual differences on the form task, but not the motion cues task, correlated with the scores on all of the social measures, suggesting that processing the global form of the walker is related to socially competent behaviour but that simply monitoring the local motion of the dots is not. The findings from both the Zhai et al. (2020) and the Miller and Saygin (2013) studies suggest that biological motion processing could possibly be considered a predictor of real-world social competent behaviour, but that this relationship may be impacted by the age of the individual, the nature of the biological motion task, as well as individual differences in motion perception.

In the present study, we examined previously published biological motion data from children and adolescents (Stubbert et al., 2023) in relation to parent reports of their real-world social competence. In doing so, we extended the literature in two specific ways. One, we assessed the relationship between biological motion processing and social competence during middle childhood and early adolescence to address whether the positive relationship demonstrated by Zhai et al. (2020) continues beyond 5-6 years of age. Two, we measured social competence using the Multidimensional Social Competence Scale (MSCS; Yager & Iarocci, 2013), a validated caregiver report that captures aspects of social functioning that are finegrained and multidimensional, and therefore may be more sensitive to variability in social cognitive skills among a non-clinical population (e.g., Yager & Iarocci, 2013; Trevisan et al., 2018) than autism screening or severity scales, such as the SRS-2 (Constantino & Gruber, 2012). Due to the importance of attending to and interpreting biological motion for the development of socially relevant skills, and evidence of the relationship found in young children (Zhai et al., 2020) and young adults (Miller & Saygin, 2013), we hypothesized that performance on the biological motion task would also positively predict social competence, as measured by parent ratings on the MSCS, in school aged children.

Method

Participants

Forty-nine school-aged children and early adolescents (24 males) ranging in age from 6-14 years (*M* = 9.57, *SD* = 2.44) were recruited from the Montreal community via online classifieds as part of a larger study. The participants had either no (*n* = 7), one (*n* = 20), two (*n* =16), three (*n* = 5), or four (*n* = 1) siblings living in their household. All of the participants reported normal or corrected-to-normal vision and no history of psychiatric or severe learning problems. Caregivers completed a general background questionnaire to collect demographic information as well as information regarding the participants' gender, vision, medical, and educational history. All of the participants had a cognitive profile, or Full-Scale IQ (FSIQ), of 80 or higher as defined by the Wechsler Abbreviated Scale of Intelligence, 2nd edition (WASI-II; Wechsler, 2011). The means and standard deviations for FSIQ (*M* = 106.27, *SD* = 13.62) were close to population parameters. The participants were screened for autism symptomology using the Social Responsiveness Scale - Second Edition (SRS-2) and removed from analyses if their T-score was above 65 (Constantino & Gruber, 2012). See Table 1 for the participant characteristics of the final group of participants included in the analyses.

Table 1

Participants' Characteristics

Variables	**Observations**	**Min-Max**	**Mean**	***SD***
Gender	M: 21, F: 24			
Age	45	6-14	9.44	2.45
FSIQ	45	80-133	106.27	13.62
Performance IQ	45	78-142	107.96	17.89
Verbal IQ	45	72-135	103.40	13.25
SRS-2 total	40	39-65	46.30	6.17
3D BM	45	12-216	49.98	44.54
MSCS total	45	235-369	315.31	32.19

Note. Minimum-maximum, mean, and standard deviations (*SD*) presented for final group of participants. See statistical analysis section for a description of the exclusion procedure. Gender (M = male, F = female), age in years, Wechsler Abbreviated Scale of Intelligence – 2nd Edition T-scores: Full-Scale IQ (FSIQ), Perceptual Reasoning Index (Performance IQ), Verbal Comprehension Index (Verbal IQ), Social Responsiveness Scale – second edition T-score (SRS-2 total), three-dimensional biological motion noise threshold (3D BM), Multidimensional Scale of Social Competence raw score (MSCS total).

Standardized Baseline Measures

Measure of Cognitive Ability

A cognitive profile was obtained for each participant using the Wechsler Abbreviated Scale of Intelligence - Second edition (WASI-II; Wechsler, 2011). The WASI-II is a clinical cognitive test that is standardized for individuals 6-89 years old and is comprised of the four subtests: Vocabulary, Similarities, Block Design, and Matrix Reasoning. Based on performance on theses subtests, a Full-Scale IQ (FSIQ) is obtained along with Verbal Comprehension (VCI) and Perceptual Reasoning (PRI) Indices, providing an estimate of verbal and non-verbal cognitive ability, respectively.

Measure of Social Behaviours

The Social Responsiveness Scale – Second Edition (SRS-2; Constantino & Gruber, 2012) is a 65-item standardized parent questionnaire designed to measure social behaviour associated with autism spectrum disorder in youths 4 to 18-years-old. An overall total score can be calculated from the treatment subscales that include Social Awareness, Cognitions, Communication, Motivation, and Repetitive Behavior. Higher T-scores indicate greater difficulty with reciprocal social interactions. Specifically, T-scores of 76 or higher are considered severe and scores between 66-75 are considered moderate, indicating clinically significant social deficits. T-scores 60-65 are in the mild range, and scores of 59 and below indicate minimal social difficulties indicative of an autism spectrum disorder diagnosis. Extensive validity data are provided, including predictive validity (sensitivity value & specificity value of .92) (Constantino & Gruber, 2012).

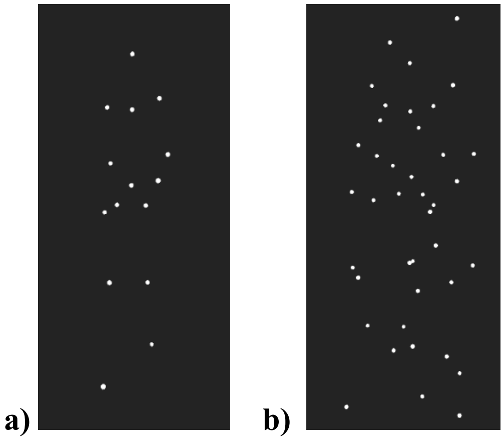
Measure of Social Perception

Three-Dimensional Biological Motion (3D BM) Task

The target stimuli consisted of point-light displays (Johansson, 1973); the dynamic representations of a walking human form composed of 15 white dots, that are intended to depict the head, shoulders, hips, elbows, wrists, knees, and ankles, against a black background (Figure 1a). The PLD was presented upright and appeared to be walking on the spot in either the left or the right direction (-16 and 16 degrees) relative to the observer, subtending 45 degrees when viewed from 100 cm. The participants were asked to indicate whether the walker was going to the left or to the right by pressing the left or right button on a bimanual response box. The duration of each trial animation was 1 second followed by a blank screen delay, with the next trial only beginning once the participant had responded. The strength or saliency of the point-light walker was manipulated by adjusting the number of interfering noise dots (Figure 1b) that were presented simultaneously with the walker. The noise dots were randomly distributed within the array, and the motion of the individual dots resembled the local movement of the individual dots comprising the intact walker. Accordingly, the walker and noise were separated only by integrating the walker's biological motion, and not by differences in the individual dot elements (Legault et al., 2012) as the size and appearance of all the dots (noise and walker) were identical. The task began without any noise, with the number of interfering dots increasing after correct responses, and vice versa. A noise threshold was determined using a 2-up 1-down staircase procedure, ending when 6 inversions had taken place (i.e., 2 correct answers followed by an incorrect answer). The threshold is the average of the number of noise dots present at each inversion. Therefore, performance is defined as the maximum number of noise dots through which the participants can accurately discriminate the direction of the point-light walker (i.e., noise threshold). The participants completed 10 practice trials of increasing difficulty (i.e., 2 trials at each noise level: 0, 25, 50, 75, and 100 dots) followed by the experimental main task. Three threshold scores were obtained from each participant, with the two most similar thresholds averaged and used in subsequent analyses.

Figure 1

Example of Stimuli from the 3-Dimensional Biological Motion Task



Note. (a) point-light walker in the left direction with no interfering dots present; (b) point-light walker (left direction) presented with 25 interfering noise dots.

Measure of Social Competence

The Multidimensional Social Competence Scale (MSCS; Yager & Iarocci, 2013)

The MSCS is a parent rating scale designed to assess social behaviours commonly observed among children on the autism spectrum who are highly verbal and have average intellectual functioning, that may also occur among neurotypical individuals. The 77 items are rated on a 5-point scale according to how much the statement describes the youth's behaviour, from 1 (*not true or almost never true*) to 5 (*very true or almost always true*). The scale measures seven distinct domains of social competence including social motivation, social inferencing, demonstrating empathic concern, social knowledge, verbal conversation skills, non-verbal sending skills, and emotion regulation. The MSCS total score, which is the sum of scores from all seven domains, was used as the outcome variable for social competence in the current study. The items are coded such that higher scores reflect higher levels of social competence. Psychometric evidence provides preliminary support for the scale's reliability and validity (e.g., internal consistency: coefficient alpha reliabilities for domains all above 0.84; Yager & Iarocci, 2013).

Procedure

The participants were tested in the McGill Youth Study Team lab at McGill University. The experimental protocol was approved by the McGill University Research Ethics Board Office, and both parental or primary caregiver informed consent and the child's assent were obtained before participation. The testing took place in a private room that included a table with two chairs for the administration of the IQ test and a laptop and 3D HDTV for the computerized tests. The testing took place over a one-hour-and-a-half session, where a battery of tests was administered, including the WASI-II and the 3D BM experimental task. Breaks were offered as necessary throughout the session. During this time, the participants' parents completed a demographics form and the social functioning questionnaires; participants were compensated for their participation.

Statistical Analyses

Three noise threshold scores were obtained from each participant and the two most similar were used as being most representative of performance. The average of these two thresholds were used in the analyses. Prior to the analyses, we excluded from the analyses the data of three participants who violated two cases of Mahalanobis, Cooks D, or high leverage, using critical values computed from the variables in the multiple regression analysis. One participant was missing the MSCS data, leaving a total of 45 participants. No participants exceeded the SRS-2 cut off of a T-score above 65, but five participants were missing SRS-2 data. A t-test suggested that participants with complete SRS-2 data ($n = 40$) did not significantly differ from those without complete SRS-2 data ($n = 5$) in MSCS scores ($t(43) = -.93$, $p = .356$), therefore those without SRS-2 data were not excluded from the study. As no significant effects of participant gender on any of the variables were found (e.g., 3D BM: $p = .220$, MSCS: $p = .967$, or SRS-2: $p = .676$), gender was excluded from further analyses. Two-way bivariate Pearson's correlational analyses were conducted to investigate the relationship between all of the variables of interest. A multiple regression analysis was conducted to explain the variance in MSCS total scores from biological motion noise threshold. Age and verbal IQ were included as covariates and biological motion as a predictor variable. In this final group of participants, the assumptions of multicollinearity, normal distribution of residuals, and high leverage for multiple regression were met. An a priori power analysis using G*Power version 3.1 (Faul et al., 2009) to determine the minimum sample size required to test the study hypothesis indicated that the required sample size to achieve 80% power for determining a medium effect at a significance criterion of $\alpha = .05$ was $N = 77$ for a multiple regression analysis with 3 predictors. Although our goal was to recruit at least that many participants we were unable to do so in a timely manner due to restrictions caused by the COVID-19 pandemic.

Results

Means, standard deviations, and two-way Pearson's correlational analyses among all the variables of interest are presented in Table 2. As higher MSCS total scores and lower SRS-2 total scores indicate greater social competence, the significant negative correlation suggests that the questionnaires are evaluating similar constructs (i.e., social competence). Age was positively correlated with 3D BM performance, but not with either measure of social competence. Three-dimensional BM performance did not correlate with either MSCS total or SRS-2 total, nor with any of the MSCS subscales ($p > 0.05$).

Table 2

Correlations between Variables of Interest

Variables	***Age***	***Verbal IQ***	***SRS-2***	***3D BM***
Age	-			
Verbal IQ	.087	-		
SRS-2 total	-.114	.089	-	
3D BM	.539*	.004	.162	-
MSCS total	.068	-.177	-.802*	-.074

Note. * Denotes statistical significance at $p < .001$. Verbal Comprehension Index (Verbal IQ), Social Responsiveness Scale-2 (SRS-2 total), three-dimensional biological motion noise threshold (3D BM), Multidimensional Scale of Social Competence (MSCS total).

To examine the extent to which biological motion performance was associated with social competence, we conducted a multiple regression analysis that looked at biological motion noise threshold as a predictor of MSCS total (Table 3). To account for individual differences among the participant groups, we controlled for effects of age and verbal IQ, which were entered as covariates. The final model predicting MSCS total was not significant: $F(3, 41) = 0.842$, $p = .479$, $R^2 = .06$, Adjusted $R^2 = -.01$.

Table 3

Standard Multiple Regressions to Predicting Social Competence from 3D BM, Age and Verbal IQ

MSCS total: $R^2 = .06$, Adjusted $R^2 = -.01$						
Predictor	***b***	**SE (b)**	***B***	**Pearson R**	**sr^2**	***P***
Constant	347.83	41.59				$p < .001$
3D BM	-0.12	0.13	-0.17	-.07	.02	$p = .359$
Age	2.30	2.38	0.17	.07	.02	$p = .341$
Verbal IQ	-0.47	0.37	-0.19	-.18	.04	$p = .216$

Note. b and B represent the non-standardized and standardized coefficients, respectively. sr^2 denotes the squared semi-partial correlation.

Discussion

The goal of the current study was to assess the association between biological motion processing and real-world social competence among children and adolescents between the ages of 6-14 years, an age range in which variable results have been found among a range of populations, including autistic children. In addition, we accounted for individual differences in verbal IQ that may impact the development of social competence. Our hypothesis that biological motion processing would positively predict social competence was not supported. Specifically, when individual differences in age and verbal IQ were considered, the model including biological motion did not significantly predict scores on the MSCS. Accordingly, we did not find evidence to suggest that performance on our 3D version of the masked direction discrimination biological motion task predicts parent ratings of real-world social competence.

Our findings appear to be inconsistent with the evidence from the previous two studies on biological motion and social competence (Miller & Saygin, 2013; Zhai et al., 2020). However, the discrepancy between the findings may be related to differences in the nature of the biological motion tasks used across studies and the age group assessed. For example, Zhai et al. (2020) who found that interactive biological motion predicted social competence particularly in the older preschool children (5-6 years old), used an interactive biological motion task rather than the more traditional single point light walker task that we used. Their interactive task, which requires participants to determine whether two point-light characters were interacting or not, may draw more strongly on the social perceptual component of biological motion, and also may better reflect real-world complex conditions. We tried to capture the complexity and ambiguity present in the social world (Birmingham & Kingstone, 2009) by introducing a 3D version of the point light walker task, which includes additional depth and object interactions (i.e., occluding and colluding) that occur in the real-world environment. These additions did not appear to compensate for the lack of an interactive social partner in the task.

Our failure to find evidence of a significant relationship between biological motion performance and social competence could also suggest that the participants focused on the motion cues of the point light walker in our 3D masked direction discrimination biological motion task, which may not be as strongly related to the social perceptual component of biological motion. Miller and Saygin (2013) used a single point light walker masked direction discrimination task that was more similar to ours, but used form (facing) and motion (walking) versions of the task. They found that asking the participants to indicate the facing direction of the walker was correlated with social measures but not when they asked them to indicate the walking direction. Thus, attending to form cues was related to social competence but attending to motion cues was not. In our task, the facing and walking direction were always congruent but were subtended at a sharper angle than those used by Miller and Saygin (2013). Accordingly, both form and motion cues were available to be integrated in order to identify the walking direction, and perhaps the participants in this age range attended more closely to the motion of the local cues (i.e., individual dots) rather than the global form of the walker. The mask of noise dots was designed to mimic the local motion of the point light walker stimuli, forcing participants to increasingly use the form cues as they proceed in the task and more noise dots are added. One point to consider in future investigations is whether the 3D space impacts the effectiveness of the noise dots in masking the local motion, given that more depth is available in the visual scene.

Our findings suggest that caution should be taken when generalizing social implications across different versions of the biological motion task. While the social cognitive implications of biological motion perception have been demonstrated (Happé et al., 2017; Pavlova, 2012), the relationship between task performance with real-world social functioning appears to be more nuanced. In the present study, the goal was to adapt the biological motion task in order to provide a more real-world experience with a 3D vantage point and add ambiguity with the noise mask. Given the novelty of this study, we are unable to ascertain whether the lack of relationship between biological motion processing and social competence is specific to our version of the task or if it reflects developmental implications of the childhood to early adolescence age range. In the future, social competence should be examined in relation to different aspects of the biological motion task in 3D space, such as simple detection, discriminating between biological motion and scrambled motion, and direction discrimination with a mask.

The specific measure of social competence can also influence outcomes. In our study, we used the MSCS questionnaire as our measure of social competence because it is considered to be sensitive in capturing finer-grained social cognitive skills (Yager & Iarocci, 2013), and does not include the sensory sensitivity and repetitive interests/behaviour items that are common in the autism screeners, making it more appropriate to use with non-clinical populations. However, even with the wider spectrum of socially specific behaviours included in the MCSC, the range of scores in our group was still relatively restricted. This may have contributed to the relatively weak association between social competence and biological motion performance. Furthermore, the MSCS is completed by the participants' caregivers and thus reflects their perceptions of their children primarily in the home environment. While the majority of the participants in this study have siblings with whom their parents could observe their social interactions, the majority of social interactions in the 6–14-year age range occurs at school. In future studies, social abilities should be assessed with additional measures, such as teacher ratings or an observation format, to try to measure social competence more holistically.

Conclusion

The aim of this study was to assess the relationship between biological motion processing and social competence, extending the neurotypical literature to include the middle childhood to adolescence developmental period. We found that when individual differences in chronological age and verbal IQ were considered, the model including biological motion did not predict social competence. Thus, while biological motion processing may be considered a hallmark of social cognition (Pavlova, 2012), the relationship between task performance and scores on measures of real-world socially competent behaviour appears to be more nuanced.

Acknowledgments

This work was supported by the Social Science and Humanities Research Council Insight grant of Canada (grant number 435-2017-1422) awarded to J.A.B. and A.B.. Additionally, this work was supported by the Fonds de recherche du Quebec - Société et Culture (FRQSC) doctoral fellowship awarded to E.S. (grant number 268636), and the Canadian Institutes of Health Research postdoctoral fellowship (grant number 176576) and the Fonds de recherche du Québec – Santé (FRQS) postdoctoral fellowship (grant number 305855) awarded to D.T. We thank the children and their parents for participating in this study as well as the experimenters, Margarita Miseros, Olivia Furholter, Jordyne Shatzky-Greenspoon, Yara Maalouf, Julia Aboud, Myriam Lesage, and Mariam Ali, who helped in data collection. We also thank Vadim Sutyushev for his assistance with programing the experimental tasks.

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Chapter VI: General Discussion

Middle childhood to early adolescence is a time of immense cognitive development and social learning, during which social interactions become more complex and goal-oriented (Monahan & Steinberg, 2011). The ability to accurately process biological motion is proposed to be a foundational skill for navigating and interacting with the real-world (Pavlova, 2012). Attending to and interpreting biological motion is thought to be an underlying mental operation of effective social communication and interactions with other people (Soto-Icaza et al., 2015). Biological motion processing is thought to be driven by a reflexive bias for socially relevant information that develops very quickly during infancy (Bardi et al., 2014). However, under complex and ambiguous experimental conditions, most reflective of real-world situations, biological motion processing appears to require effortful and controlled attentional processing and may follow a developmental trajectory that continues through childhood and into adolescence (Hadad et al., 2011). The overall objective of this dissertation was to explore the development of biological motion processing in childhood and adolescence. Thus, in order to obtain a more nuanced understanding of the contributing factors for the development of biological motion processing, children and adolescents aged 6 to 14 years completed a 3-dimentional (3D) masked direction discrimination point light walker biological motion task.

The objective of the first manuscript was to explore possible contributions of dynamic attention in the cross-sectional development of biological motion processing. This was accomplished by examining the developmental relationship between performance on the 3D biological motion task and that on a 3D version of the multiple object tracking (MOT) task. The concurrent examination of these two tasks also allowed for an initial assessment of the pattern of task performance improvements with age. Performance on the 3D MOT and masked direction discrimination biological motion tasks was found to be positively correlated and both improved with age. The positive correlation between biological motion processing and age highlights that, despite the very early emergence of a reflexive sensitivity to perceiving biological motion among infants (Bardi et al., 2014; Simion et al., 2011), young children are less skilled than adolescents in attending to and discriminating the direction of biological motion information presented in noise. In addition, performance on the MOT task was significantly related to biological motion performance, suggesting a possible overlapping dynamic attention mechanism underlying both tasks that allows for attention to be allocated to information that is in motion. Finally, the relationship in performance between the two tasks did not differ as a function of age, suggesting that the disparity in the social nature of the tasks did not lead to any measurable differences in the developmental trajectories of task performance during middle childhood to early adolescence.

The goal of the second manuscript was to examine the social perceptual component of biological motion processing. Specifically, the focus was on the link between biological motion processing and real-world social competence in children and adolescents, as indicated by parent ratings on the Multidimensional Social Competence Scale (MSCS). We also accounted for individual differences in verbal ability that may impact the development of social competence. Contrary to our hypothesis, we did not find evidence to suggest that performance on our 3D version of the masked direction discrimination biological motion task predicted real-world social competence. A number of possibilities could explain these null results that are inconsistent with those of the previous studies of biological motion processing and social competence (Miller & Saygin, 2013; Zhai et al., 2020), including the nature of the biological motion task used, developmental implications of the childhood to early adolescence age range, or the limited variability in the parent ratings of social competence. Nonetheless, these findings highlight that the relationship between task performance and scores on measures of real-world socially competent behaviour appears to be more nuanced.

Overall, the findings of the two manuscripts suggest that the developmental trajectory of performance on the 3D masked direction discrimination biological motion task into adolescence may be largely attributable to the more general development of dynamic visual attention. Whereas biological motion may be considered a hallmark of social cognition (Pavlova, 2012), the link between biological motion processing and real-world socially competent behaviour is complex and needs to be further explored.

Visual Attention and Biological Motion Processing

The contribution of attention and effortful control in the processing of biological motion has been debated (Safford et al., 2010). For this dissertation, a direction discrimination biological motion task that was presented with increasing noise was used, which has been suggested to require the use of attention for effective processing (Thornton et al., 2002). The evidence for the role of attention in biological motion processing emerged from studies in which the selective component of attention was found to be implicated in performance (Cavanagh et al., 2001, Chandrasekaran et al., 2010; Ji et al., 2020). However, the dynamic component of attention that is key to performing a biological motion task was not adequately represented. Thus, we chose to examine the contribution of attention using the MOT task, which involves simultaneously focusing on and tracking objects as they move among distractors objects in a random manner (Pylyshyn & Storm, 1988). In manuscript 1, we found that performance on the biological motion and 3D-MOT tasks were positively related and follow similar developmental trajectories, suggesting some overlap in the mechanisms of processing between the two tasks. Specifically, the 3D-MOT speed threshold (i.e., the average speed with which 3 target objects could be accurately tracked) was related to the biological motion noise threshold (i.e., the average number of noise dots through which the direction of the walker could accurately be perceived). While the 3D-MOT task is also considered to involve selective attention (Scholl, 2009), it is also first and foremost a dynamic task (i.e., speed threshold), and therefore an excellent metric of dynamic attention (Meyerhoff & Papenmeier, 2020). Thus, the relationship between the 3D biological motion and MOT task performance helps delineate the specific attentional components, suggesting that in addition to selective attention, dynamic attention is also involved in the processing of biological motion. This finding also has implications for the cascading effect that biological motion has on later social development, as difficulties with dynamic attention may disrupt the social learning that occurs through biological motion processing (Blake & Shiffrar, 2007; Johnson et al., 2005). Our findings are specific to development from middle childhood to early adolescence, throughout which both MOT and biological motion performance were found to improve.

The comparison of development of 3D MOT and biological motion performance also has implications for the development of “social” versus “non-social” attention, that is attention that is allotted to information that is socially relevant (e.g., human walker) versus elements of the environment that are not inherently social (e.g., objects). Specifically, according to the dynamic systems theory of attention (Ristic & Enns, 2015), attention is both the cause and the outcome of the interplay between the individual and the environment, in which the individual may prioritize and efficiently attend to information based on many factors, such as the information’s content or nature. We considered that biological motion processing might develop differently than MOT because of the social nature of the stimuli. Based on Hirai and Senju’s (2020) two-stage process model of biological motion processing, the reflexive orienting support from the initial ‘Step Detector’ system could have contributed to a unique and possibly accelerated developmental trajectory of attention for biological motion as compared to the development of attention to non-social motion, such as with the spheres in the 3D MOT. We did not find evidence of this in the cross-sectional developmental trajectories of the tasks. This is not to say that the social component did not impact development, simply that it did not result in a different trajectory than that of the MOT task. This finding could suggest that our masked direction discrimination biological motion task may not tap into the global and social perceptual processing that may uniquely influence cognitive development, and instead is more dependent on attentional processing.

Measurement of Biological Motion

Increasing the complexity of the direction discrimination biological motion task by adding a mask and presenting it in 3D allows for conditions more similar to the real-world environment, but also leads to increased difficulties in deconstructing and determining the unique contribution of specific factors to performance. In the context of Hirai and Senju’s (2020) two-stage model of biological motion processing, our findings suggest that this task requires the secondary “Bodily Action Evaluator” (BAE) system, which is used to process configural information specific to human actions that has been learned through experience and is modulated by attention. Specifically, the gradual improvement in performance between childhood and early adolescence that we observed on our masked direction discrimination task is evidence of the use of the BAE system. However, the direction discrimination component of the task may also be facilitated by the more reflexive “Step Detector” (i.e., local motion of the feet) (Chang & Troje, 2009). Miller and Saygin (2013) found that their form task (i.e., facing direction) predicted real-world social competence, but their motion task (i.e., walking direction) did not. The lack of relationship with the social competence measure in our study could possibly indicate that our version of the biological motion task was completed primarily by interpreting the local motion of the feet or steps (i.e., using the Step Detector). The common noise threshold technique that we used, in which noise dots are slowly added with accurate responses, may have resulted in an outcome variable that reflects local motion as opposed to global form processing. This may also be evidenced by the relationship that was found between the direction discrimination biological motion task and MOT task performance, in that the dots that represent the feet in the walker have the longest movement trajectory (Chang & Troje, 2009), and thus may require the most dynamic attention. To help clarify which cues are being attended to, the participants could be explicitly asked where they found themselves looking while completing the biological motion task. Alternatively, future research could involve eye tracking to determine the participants' primary focal point while completing the biological motion task, which would offer valuable insight into the processing mechanisms being used. Developmental differences could also be explored with this technique (Hochhauser et al., 2023).

Implications for Neurodivergent Development

Our findings also have implications for research with populations in which unique characteristics in attention and social functioning are key clinical markers, such as people on the autism spectrum or with attention deficit /hyperactivity disorder (ADHD). In the case of neurodivergent development, differences in attentional to social stimuli and in turn biological motion, may impact the amount or quality of social experiences that individuals engage with in their environments. This could in turn reduce the developmental specialization that is seen in neurotypical children and ultimately lead to a different way of processing and interpreting biological motion (Foglia et al., 2022; Kröger et al., 2014). Accordingly, studies of biological motion processing across the lifespan are essential for testing the relationship with attention and social functioning in these populations. The examination of developmental patterns both better encapsulate the individual differences and highlights how styles and biases for perceiving and attending to biological motion change with age.

In the case of autistic individual, an observed decreased sensitivity to biological motion in has been suggested to be related to the way that motion is perceived more generally (e.g., Koldewyn et al., 2011; Van der Hallen et al., 2019). However, Annaz et al. (2010) found that the perception of biological motion may be specifically affected among autistic individuals, developing differently regardless of perceptual abilities on other motion tasks. They suggested that the social nature of the biological motion stimuli may contribute to the differences in development of sensitivity between groups. Accordingly, in future studies the use of both the biological motion and the MOT tasks, characterized by their complex and dynamic content, would help clarify the impact of motion and nature of the stimuli (i.e., non-social vs. social) on dynamic visual attention. This information would shed light on the attentional styles and processing biases that neurodiverse individuals use when navigating their environments.

Implications for Practitioners

Whereas our complex version of the direction discrimination task did not predict parent ratings of social competence, we did find that dynamic attention may be related to the ability to perceive the motion of others. This finding has implications for educators and school practitioners (and anyone who is trying to support social development). Specifically, helping children focus their attention to the subtle body motions of those with whom they are interacting with may help support their interpretation of others' intentions. Explicitly breaking down the messages that are communicated through these motions will help draw their attention to this information. Social stories are commonly used to help children learn about and prepare for ways to navigate social interactions (Karkhaneh et al., 2010). These stories are typically presented in comic or book format, which is helpful for providing a visual representation of the social scenario. However, this format is missing the motion cues that also include helpful information for interpreting and responding appropriately in social interactions. Thus, social training should also include dynamic stimuli, such as videos and even role playing, to help foster the attention to the motion cues. Virtual reality social training is another format that capitalizes on the dynamic component of biological motion. The use of virtual reality technology allows for the student to safely have completely immersive yet controlled role-playing social experiences (Yang et al., 2017). There is some preliminary evidence to suggest that virtual reality social training protocols are feasible and are effective in improving social cognitive skills (Didehbani et al., 2016; Kandalaft et al., 2013).

Limitations

Although we extended the literature to include a concurrent measurement of MOT and biological motion, allowing for the investigation of individual differences, the cross-sectional design limits our ability to make claims about biological motion processing over time. Longitudinal examination of biological motion preference and processing in the first 2 years of life has demonstrated changes from reflexive to effortful and motivation driven processing during this early period of life (Sifre et al., 2018). Thus, a longitudinal study throughout middle childhood to early adolescence may shed light on developmental changes as well as individual styles of processing.

The robustness of the PLD biological motion paradigm has allowed for significant diversity in the investigation of this phenomenon. However, this significantly limits potential comparisons with previous studies. Because there are so many contributing factors, the slightest adjustment to the protocol may change the mechanisms through which the motion is being processed. For example, adjusting a noise mask from moving with the dots to instead being a grid in front of the dots is thought to change the same task from requiring global to requiring local processing (Chang & Troje, 2009). Slight differences in the protocol across biological motion studies make it difficult to develop hypotheses that are based on consistent findings and may also reflect the amount of variability in finding across studies. Additionally, this diversity in biological motion tasks is not reflected in statements about biological motion processing ability, as it is commonly (and as is the case in this dissertation) referred to as a single phenomenon. This is particularly problematic when discussing atypical populations and making claims about their biological motion processing abilities. Our finding that the 3D masked direction discrimination task is not related to real-world social competence suggests that caution should be taken when generalizing social implications across different versions of the biological motion task. As such, the processing of biological motion is not a single phenomenon and a number of different levels through which it can be processed is reflected in the variability with which it is measured (Troje, 2008). Given the variability of performance across studies, researchers need to be particularly cognizant of how task protocol can alter the demands required for completing the task.

Directions for Future Research

While the social cognitive implications of biological motion perception have been demonstrated (Pavlova, 2012), the relationship between task performance with real-world social functioning appears to be more nuanced. We did not find a significant relationship between the 3D masked direction discrimination biological motion task performance and parent ratings on the Multidimensional Scale of Social Competence. Given the novelty of this study, we are unable to ascertain whether this is specific to our version of the task or if it reflects developmental implications of the childhood to early adolescence age range. To try to explore this nuance in the future, social competence should be examined in relation to different aspects of the biological motion task in 3D space, such as simple detection, discriminating between biological motion and scrambled motion, and direction discrimination with a mask (Troje, 2013). This will help determine which version, if any, are appropriate measures of social perceptual abilities in neurotypical children and adolescents.

This is one of the first times this masked direction discrimination task has been presented in a 3D format. While the motion of the mask was made to mimic the local motion of the target dots, the additional ocular distance may have altered the impact of the mask. The participants may have had more access to the local cues and were able to avoid using global cues for as long as possible while the noise dots increased. This could possibly lend some insight as to what occurs in the real-world environment, if indeed 3D perspectives lend more to local processing of biological motion than global processing. Our findings also highlight that performance on the 3D version of the biological motion tasks is associated with age-related improvements until around early adolescence, the age range at which performance seems to be adult-like on the 2D detection version of this task (Annaz et al., 2010). However, researchers need to consider Hadad et al.'s (2011) finding that improved performance on a biological motion task reflected a quadratic trend as a plateau was observed to begin around age 13 years continued until 25 years of age. Thus, future studies should compare performance on the 2D and 3D versions of this masked direction discrimination task to determine if the dimension impacts performance while also extending the age range to see if a similar trend emerges.

Chapter VII: Final Summary and Conclusion

The focus of this dissertation was to obtain a more nuanced understanding of the contributing factors for the development of biological motion processing among children and early adolescents. Specifically, we were interested in the role of dynamic attention in performance on a 3D masked direction discrimination version of the biological motion task, and the link to real-world social processing and behaviour. The findings from Manuscript 1 of this dissertation highlight that the visual attention skills required for discriminating the direction of the movements of others (i.e., biological motion) continue to develop through childhood into adolescence. Furthermore, we offer preliminary evidence that biological motion and MOT attentional abilities improve similarly across age, suggesting concordant dynamic attention developmental trajectories. In Manuscript 2 we did not find evidence of a relationship between task performance and scores on a measure of real-world socially competent behaviour (i.e., MSCS) during the middle childhood to adolescence, despite biological motion being considered a hallmark of social cognition (Pavlova, 2012). Overall, these findings on the development of biological motion processing shed additional light on the contribution of attention and suggest that the varying demands of the biological motion tasks should be considered in order to better illustrate the real-world social implications of the processing of this motion.

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