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Exploration de la Prédiction Temporelle associée à la Motricité chez les Individus Neurotypiques et Neuro-atypiques

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LISTE DES ABREVIATIONS

ANOVA : Analyse de la Variance

CIUSSS : Centre Intégré Universitaire de Santé et de Services sociaux

CMS : Common Mode Sense

CNV : Contingent Negative Variation

CPP : Comité de Protection des Personnes

DRL : Driven Right Leg

DSM : Diagnostic and Statistical Manual of Mental Disorders

EEG : Electroencéphalographie

fMTP : formalized Multiple trace theory of Temporal Preparation

fNART : french National Adult Reading Test

FP : Foreperiod

HR : Haut-Risque de conversion psychotique

ICA : Independent Component Analysis

ITI : Inter Trial Interval

LRP : Lateralized Readiness Potential

OSF : Open Science Framework

RT : Reaction Time (TR pour Temps de Réaction dans les parties francophones)

SANS : Scale for the Assessment of Negative Symptoms

SAPS : Scale for the Assessment of Positive Symptoms

SD : Standard Deviation

SEM : Standard Error of the Mean

SZ : Schizophrénie

T-test : Test de Student

À mon grand-père maternel, qui n'est plus là mais qui veille sur moi.

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LISTE DES PUBLICATIONS

Arrouet, A., Polgári, P., Giersch, A., & Joos, E. (2022). Temporal Order Judgments in Schizophrenia and Bipolar Disorders – Explicit and Implicit Measures. Timing & Time Perception, 11(1-4), 362-385. https://doi.org/10.1163/22134468-bja10071

Cet article n'apparaît pas dans le corps principal de la thèse car il aborde un aspect différent de la temporalité : le traitement de l'ordre temporel. Cependant, il traite également des effets séquentiels et est inclus en annexe.

Arrouet, A., Marques-Carneiro, E., Marquet, P., Giersch, A., (soumis à NeuroImage). Task-Specific Temporal Prediction Mechanisms Revealed by Motor and Electroencephalographic Indicators.

Des révisions mineures ont été demandées par l'éditeur de NeuroImage, après une première révision. L'article a été révisé et resoumis. C'est cette dernière version révisée qui figure dans le manuscrit de la thèse.

Arrouet, A., Marques-Carneiro, E., Marquet, P., Giersch, A. Distinct Maturation of Motor and Sensorimotor Temporal Predictions Throughout Neurodevelopment. En préparation.

Arrouet, A., Marques-Carneiro, E., Giersch, A., Marquet, P. Temporal Prediction Tasks Reveal Sensorimotor Alterations in Children and Adolescents at Genetic High Risk for Psychosis. En préparation.

Ces deux articles ont été rédigés et figurent dans le manuscrit de la thèse dans leur état actuel d'avancement.

1. INTRODUCTION GÉNÉRALE

Le but initial de cette thèse était appliqué, c'est-à-dire comprendre les mécanismes d'altération du sens de soi corporel dans la schizophrénie (SZ) (Ferri et al., 2014; Martin et al., 2017; Parnas & Handest, 2003; Sandsten et al., 2020). Dans ce but nous avons construit un nouveau protocole, adapté d'une expérience bien connue dans la littérature (la 'variable foreperiod' que nous appellerons 'tâche d'attente temporelle' dans les parties francophones de ce manuscrit) (Capizzi et al., 2015; Karlin, 1959; Niemi & Näätänen, 1981; Vallesi & Shallice, 2007). Nous pensions simplement adapter la tâche pour la rendre plus pertinente pour étudier les troubles cognitifs liés au sens de soi corporel. Nous avons donc ajouté une composante motrice et tactile à la tâche d'attente temporelle. Mais nous sommes allés de surprise en surprise. Cette thèse résume ces surprises et comment nous les avons interprétées. Les résultats ont amené à des questions fondamentales, même si ce n'était pas l'objectif initial. Les travaux ont donc nécessité plusieurs ajustements successifs, et une littérature chaque fois nouvelle, comme l'intégration sensorimotrice, ou les effets du neurodéveloppement. La littérature est développée dans l'introduction spécifique de chaque travail, parce qu'il semblait plus simple de présenter le développement des études dans l'ordre chronologique plutôt que d'annoncer toutes les surprises à l'avance dans l'introduction générale. Celle-ci inclue donc principalement les connaissances de base dont nous sommes partis, et plus particulièrement, des concepts du temps en psychologie expérimentale.

Le temps est omniprésent dans notre environnement et influence l'ensemble de nos comportements. Notre perception est celle d'un temps unique, qui s'écoule inexorablement. Cependant, il n'est pas certain que le cerveau utilise un mécanisme temporel unique (Mauk & Buonomano, 2004). Il pourrait faire appel à des processus distincts (Buhusi & Meck, 2009; Buonomano & Laje, 2010; Garavaglia et al., 2024) et certains auteurs ont proposé des mécanismes locaux, par exemple spécifiques aux différentes modalités sensorielles (Gamache & Grondin, 2010; Mioni et al., 2016), à des tâches différentes (Ivry, 1996) ou à des durées différentes à estimer (Grondin et al., 1999). Dans ce travail nous nous intéressons à la façon dont nous ajustons nos actions dans le

temps selon les contextes. Par exemple, lorsque l'on est arrêté à un feu rouge, nous attendons que le feu passe au vert pour démarrer notre voiture. Nous anticipons à la fois le moment où le feu changera de couleur et le moment où nous appuierons sur l'accélérateur. Une question fondamentale de la littérature, encore non résolue, est de savoir si les mêmes mécanismes d'anticipation temporelle nous préparent à la fois à percevoir le feu vert et à appuyer sur la pédale (Correa et al., 2006a; Ramirez et al., 2021; Thomaschke et al., 2011; Volberg & Thomaschke, 2017). En d'autres termes, selon que l'on attend un événement perceptif (le feu passant au vert) ou moteur (appuyer sur la pédale), s'agit-il des mêmes mécanismes temporels qui entrent en jeu ? Les résultats que nous avons obtenus avec notre nouvelle tâche d'attente temporelle nous ont conduits à explorer cette question chez des individus neurotypiques. Cet objectif a été abordé dans les études 1 et 2.

La deuxième partie de la thèse s'est intéressée aux populations neuro-atypiques, dans le but d'utiliser notre tâche pour mieux comprendre les différents types de troubles de la préparation temporelle en condition pathologique. Notre étude s'est concentrée sur la SZ, une condition caractérisée par un ensemble de symptômes complexes qui touchent au sens de soi (Ferri et al., 2014; Martin et al., 2017; Parnas & Handest, 2003; Sandsten et al., 2020), mais aussi par des altérations du contrôle moteur (Térémetz et al., 2017), notamment lors de la planification de séquences motrices complexes (Delevoye-Turrell et al., 2007; Giersch et al., 2016; Peralta et al., 2010; Walther & Strik, 2012). Une séquence motrice est un enchaînement ordonné de sous-mouvements coordonnés pour produire un mouvement fluide. La bonne exécution de ces séquences repose sur la capacité à organiser les sous-mouvements dans un ordre temporel précis. Un manque de cohérence temporelle pourrait compromettre la préparation et l'exécution des mouvements complexes. Des déficits moteurs seraient d'ailleurs déjà présents avant le développement de la maladie, chez des individus ayant un haut-risque (HR) génétique de développer la pathologie (Damme et al., 2024; Delevoye-Turrell et al., 2012; Manschreck et al., 2015). Il a été suggéré que les troubles de la programmation motrice pourraient contribuer aux déficits moteurs observés chez les individus atteints de SZ (Delevoye-Turrell et al., 2007) et plus particulièrement, les troubles de préparation temporelle (Giersch et al., 2016). Notre protocole nous a permis d'explorer cette hypothèse.

Le second objectif, d'ordre clinique, était d'examiner les mécanismes de préparation temporelle dans le contrôle moteur chez les populations considérées comme neuro-atypiques. Il a été exploré dans les études 3 et 4. Cet objectif requiert un développement sur les mécanismes qui permettent la préparation temporelle, et plus particulièrement les liens entre passage du temps et prédiction temporelle.

1.1. Lien entre passage du temps et prédiction temporelle

Le temps s'écoule de manière continue, sans interruption entre les moments qui constituent nos vies. Pourtant, le moment présent est perçu comme un instant unique, une pause dans cette continuité temporelle. Ces deux impressions sont contradictoires, ce qui soulève la question de leur coexistence (Wittmann, 2011). L'exemple de la mélodie proposé par Husserl (1991) permet de comprendre comment les capacités de prédiction temporelle concilient la notion d'instant présent et le sentiment de continuité temporelle. Lorsque nous écoutons une mélodie, la ligne de la mélodie est définie par la note passée (dont nous nous souvenons), la note présente, et la note future (que nous anticipons). Nous sommes conscients des trois notes au même instant. Si chaque note était perçue isolément, il serait impossible de reconnaître la mélodie. De même, notre perception du temps est un processus dynamique qui intègre les moments passés et présents pour anticiper ceux à venir et nous procurer une sensation de continuité temporelle (Fuchs, 2007). Par ailleurs, anticiper les évènements de son environnement permet de s'y préparer et d'y répondre de manière optimale. Cette préparation temporelle est essentielle pour adapter son comportement à diverses situations quotidiennes. Reprenons l'exemple d'une voiture arrêtée à un feu rouge. À mesure que le temps passe, la probabilité que le feu passe au vert augmente, tout comme le niveau de préparation pour démarrer la voiture. Cette préparation permet de réagir plus rapidement, c'est-à-dire de démarrer la voiture dès que le feu passe au vert, évitant les désagréments de klaxons impatients. La manière dont le passage du temps permet d'optimiser la préparation à un évènement prédictible est opérationnalisée en laboratoire grâce aux tâches d'attente temporelle.

Avant d'évoquer comment l'attente temporelle est mesurée, nous résumons brièvement la question du contenu de cette attente, c'est-à-dire la façon dont la durée est évaluée. En effet, quand on attend que le feu passe au vert, il n'est pas nécessaire de penser au temps, on parle alors d'attente implicite. Néanmoins, si le feu tarde à passer au vert, on ressent

de l'impatience. Ceci montre que la durée a été évaluée, et qu'elle joue un rôle dans l'attente. La question des mécanismes d'évaluation de la durée va au-delà des objectifs de la thèse. Nous l'évoquons brièvement en raison de l'importance des modèles proposés pour expliquer la perception de durée.

1.2. Évaluation du passage du temps

L'évaluation explicite de la durée se distingue de la perception implicite dans la mesure où elle requiert d'estimer explicitement la durée écoulée. De nombreuses expériences permettent d'évaluer ces capacités d'estimation temporelle à travers des tâches perceptuelles ou motrices. Par exemple, dans des tâches de jugement de durée, les participants comparent deux intervalles de temps définis par un stimulus de début et de fin, et indiquent si ces durées sont équivalentes et, le cas échéant, laquelle est la plus longue. Ces tâches peuvent également inclure une composante motrice, comme dans les tâches de reproduction motrice. Dans ce cas les participants doivent reproduire une durée de référence en appuyant sur un bouton au début et à la fin de cette durée (Droit-Volet, 2022; Kononowicz & Penney, 2016).

Une question centrale est : quels mécanismes cérébraux sous-tendent l'estimation du temps ? Le premier modèle, proposé par Treisman (1963), est celui de l'horloge interne, qui comprend un interrupteur contrôlé par l'attention, un pacemaker produisant des impulsions régulières, et un accumulateur, qui comme son nom l'indique, accumule ces impulsions. Au début de la durée à estimer, l'interrupteur se ferme, permettant l'accumulation des pulsations. À la fin de la durée, l'interrupteur s'ouvre, arrêtant ainsi l'accumulation. La durée subjective dépendrait donc du nombre de pulsations.

Cependant, de nombreuses études ont contesté l'idée d'une horloge unique (Ivry & Schlerf, 2008). De nombreux auteurs ont en effet montré que les performances d'estimation temporelle varient en fonction de l'activité réalisée ou même de la modalité sensorielle impliquée, et suggéré l'existence d'horloges multiples (Bueti, 2011; Bueti et al., 2008; Gamache & Grondin, 2010; Grondin & Rousseau, 1991; Toso et al., 2021). De plus, de nombreuses aires cérébrales sont impliquées dans différentes tâches temporelles (Coull, 2009; Coull et al., 2013, 2014, 2016; Coull & Giersch, 2022; Koziol et al., 2014; Macar et al., 2006; Nozaradan et al., 2017) : par exemple, les ganglions de la base sont

impliqués dans la perception explicite du temps, mais aussi dans la perception des rythmes. Le cortex pariétal et le cortex préfrontal jouent un rôle dans l'estimation de durée, mais aussi dans l'évaluation des probabilités d'occurrence d'un stimulus avec le passage du temps. Le cortex pariétal serait également impliqué dans la perception de l'ordre temporel. Le cervelet joue un rôle dans l'estimation de durée ainsi que dans la coordination motrice et le séquencement des mouvements. L'aire motrice supplémentaire pourrait jouer un rôle dans l'extraction explicite des durées. Cette diversité a donné lieu à des modèles alternatifs à celui du modèle de l'horloge.

Le modèle de Buonomano (Buonomano, 2000; Buonomano & Karmarkar, 2002; Karmarkar & Buonomano, 2007) propose que la perception du temps découle non seulement de neurones spécifiques, mais également de l'activité et des interactions de ces neurones au sein de réseaux. Dans cette perspective, le temps est codé par la structuration temporelle de l'activité neuronale (les 'patterns'), chaque instant étant lié à une configuration unique. Ce modèle met en avant le caractère dynamique et plastique de notre perception temporelle, qui s'ajuste en fonction des exigences de la tâche et de nos expériences antérieures (Hardy et al., 2018). Ce modèle rejoint des données expérimentales qui suggèrent que notre perception explicite du temps se développe implicitement à travers nos actions (Coull & Droit-Volet, 2018).

Ces modèles et résultats concernent la perception explicite du temps, mais ils se rapportent à la question initialement soulevée par cette thèse, à savoir : l'existence de mécanismes multiples de la perception du temps, et qui fonctionnent en parallèle.

1.3. Tâche d'attente temporelle et marqueurs de la prédiction temporelle

Contrairement aux tâches d'évaluation de durée, qui requièrent un jugement explicite sur la durée écoulée, les tâches d'attente temporelle ne nécessitent pas ce type de jugement. Comme nous l'avons précédemment mentionné, ces tâches sont implicites. Le moment d'occurrence d'un événement est prédit automatiquement afin de s'y préparer au mieux. La prédiction peut être basée sur les événements récents, par exemple l'estimation d'une probabilité de survenue de l'événement. Cette estimation peut être basée sur l'ensemble des événements passés (la distribution), ou sur les occurrences récentes (ce qui s'est passé

juste avant). Par exemple si une lumière rouge est toujours suivie par une lumière verte, l'attente de celle-ci sera forte. En revanche, si la lumière verte est un événement rare, son apparition ne sera pas nécessairement anticipée. De même, si la lumière verte survient toujours moins de deux secondes après la lumière rouge, l'attente disparaîtra après ce délai (Correa et al., 2006b).

Expérimentalement, les tâches d'attente temporelle reposent sur le principe suivant : un premier signal est présenté aux participants, suivi, après un délai court ou long, d'une cible. Les participants doivent réagir le plus rapidement possible à l'apparition de la cible, généralement en appuyant sur un bouton réponse. Le temps de réaction (TR) sert d'indicateur comportemental pour mesurer les performances dans ce type de tâche. Le bénéfice du passage du temps, l'un des marqueurs des capacités de prédiction temporelle, se manifeste sur les TRs de la manière suivante : plus la cible survient après un délai long, plus le niveau de préparation des participants est élevé, plus les TRs sont rapides (Coull, 2009; Han & Proctor, 2022; Johnson et al., 2015; Niemi & Näätänen, 1981; Zahn & Rosenthal, 1966). L'une des explications possibles est la prise en compte de la probabilité d'occurrence de la cible (Janssen & Shadlen, 2005; Nobre et al., 2007). En effet, dans le cadre de la 'hazard function', il y aurait un calcul automatique de la probabilité conditionnelle qu'un événement se produise alors qu'il ne s'est pas encore produit. Ce modèle explicatif rend compte des manipulations de probabilité d'occurrence des cibles. Un modèle alternatif a été développé pour expliquer pourquoi les TRs sont plus rapides au délai long qu'au délai court. Selon le modèle formalisé des traces multiples de la préparation temporelle (fMTP), cette préparation est influencée par les traces mémorielles laissées par les essais précédents. Ces traces mémorielles contribuent à optimiser la préparation du système moteur, facilitant ainsi la réaction à l'apparition de la cible (Los et al., 2014, 2017; Salet et al., 2022). Cet effet rend également compte d'influences d'essai en essai.

En effet, dans les tâches d'attente temporelle, le délai d'apparition de la cible varie d'un essai à l'autre, et le délai de l'essai précédent influence les performances à l'essai suivant, un phénomène appelé 'effets séquentiels' (Los & Heslenfeld, 2005; Steinborn et al., 2008; Van der Lubbe et al., 2004; Woodrow, 1914). Ces effets, robustes et automatiques, reposent sur la prédiction que deux essais consécutifs seront similaires (Kong et al., 2015; Vallesi et al., 2014), ou sur les effets mémoriels dans le modèle fMTP. En tenant compte

des probabilités de l'occurrence de la cible, après un essai avec un délai long, le délai suivant est prédit comme étant long. Si le délai suivant est finalement court, la cible survient plus tôt que prévu, ce qui induit un effet de surprise (non conscient) et un ralentissement des TRs. Plus précisément, un TR plus lent est observé après un délai court précédé d'un délai long (séquence long-court) comparé à deux délais courts consécutifs (séquence court-court). Ces effets séquentiels sont dits asymétriques car l'influence du délai précédent sur le TR n'est présente que lorsque le délai de l'essai actuel est court (Capizzi et al., 2015; Karlin, 1959; Los, 2010; Mento, 2017). Lors d'un essai avec un délai long, même si le délai précédent était court et que les participants prédisent une apparition de la cible au délai court, cela n'affecte pas leur performance. Même si la cible ne survient pas au délai court, la préparation est maintenue jusqu'au délai long, assurant ainsi un TR optimal lorsque la cible intervient.

Les explications pour les effets séquentiels sont similaires pour le modèle fMTP et le modèle qui tient compte des probabilités d'occurrence de la cible. La principale différence est que l'implication de la mémoire dans le modèle fMTP permet de se détacher des mécanismes de prédiction. Une discussion sur ces modèles va au-delà des objectifs de cette thèse. Nous ne manipulons pas les probabilités d'occurrence des cibles, toujours à 100%, et nous utilisons les influences d'essai en essai comme un outil pour explorer nos questions. Leurs mécanismes sous-jacents ne font pas l'objet de notre travail. Nous devons cependant reconnaitre une influence forte du modèle qui tient compte des probabilités d'occurrence de la cible sur notre travail, ce qui nous conduit à mentionner fréquemment le terme de 'prédiction' temporelle.

Les effets observés pendant les tâches d'attente temporelle sur les TRs peuvent être également observés sur un indicateur électroencéphalographique (EEG) classiquement mesuré dans les paradigmes d'attente temporelle : la variation contingente négative (CNV) (Los & Heslenfeld, 2005; Mento, 2017; Mento et al., 2013; Trillenberg et al., 2000).

1.4. Un indicateur EEG de la prédiction temporelle

La CNV a été décrite pour la première fois par Walter et al. (1964) comme un potentiel évoqué par un premier stimulus, qui persiste jusqu'à l'occurrence d'une cible qui peut

être prédite dans le temps. Elle a initialement été interprétée comme un indicateur de préparation temporelle, impliquant des processus moteurs et cognitifs. Certains auteurs ont utilisé des indices attentionnels qui indiquent le délai auquel la cible arrive (Coull & Nobre, 2008; Mento, 2017). Ils ont montré que l'amplitude de la CNV est plus négative lorsque les participants savent quand la cible va arriver, comparativement à une condition dite neutre où cette information n'est pas disponible (Griffin & Nobre, 2003; Mento, 2017; Mento & Vallesi, 2016). Cette modulation de la CNV a été interprétée comme un marqueur de préparation motrice proactive, reflétant une anticipation optimisée de la réponse à fournir.

La CNV ne reflète pas uniquement des processus moteurs ou attentionnels; son amplitude est influencée par d'autres processus cognitifs, dépendant du type de tâche temporelle considéré. Par exemple, dans les tâches temporelles explicites, les participants doivent évaluer consciemment le temps écoulé (Kononowicz & Penney, 2016), en comparant deux durées écoulées ou en reproduisant une durée mémorisée. Cette focalisation sur la durée se traduit par une variation de l'amplitude de la CNV (Giovannelli et al., 2014; Macar et al., 1999; Pfeuty et al., 2008). Kononowicz & van Rijn (2015) ont proposé que la CNV reflète des processus décisionnels à l'œuvre dans l'évaluation de durée. Ces résultats suggèrent que ce potentiel évoqué intègre non seulement la perception consciente du temps, mais aussi des processus cognitifs de haut niveau, tels que l'attention, la mémoire de l'intervalle temporel appris et la prise de décision (Arjona et al., 2014; Brunia, 1993; Ng et al., 2011; Wiener & Thompson, 2015).

La CNV reste un indicateur EEG privilégié pour l'étude des capacités de prédiction temporelle, car les mécanismes sous-jacents à sa genèse peuvent être dissociés des processus moteurs et décisionnels. Mento (2013) a utilisé une tâche d'attente temporelle dans laquelle aucune réponse motrice n'était requise à l'occurrence de la cible. Dans cette tâche, le délai était constant d'essai en essai, mais variait entre les blocs expérimentaux. Une CNV a été observée tout au long du délai précédant l'occurrence de la cible, avec une amplitude croissante au fil des essais, reflétant un apprentissage progressif de la structure temporelle du bloc expérimental. Cet apprentissage implicite s'est manifesté même en l'absence de réponse motrice ou de prise de décision, suggérant que la CNV reflète une forme de prédiction temporelle indépendante des processus de décision et de réponse.

L'amplitude de la CNV est également sensible aux effets séquentiels : avant l'occurrence de la cible au délai court, la CNV est plus négative si le délai de l'essai précédent était également court plutôt que long. Comme pour les effets séquentiels observés sur les TRs, ces effets sur la CNV sont asymétriques, car l'amplitude de la CNV au délai long n'est pas affectée par le délai de l'essai précédent (Los & Heslenfeld, 2005; Mento, 2017; Mento et al., 2013; Van der Lubbe et al., 2004).

La CNV est donc bien pertinente pour les tâches d'attente temporelle. L'implication relative des processus perceptifs et/ou moteurs n'est pas toujours claire cependant. Cette question est importante pour la CNV comme pour les réponses comportementales. Certaines études décrites ont été réalisées avec des tâches dans lesquelles il a été observé que les capacités de prédiction temporelle influençaient les processus perceptifs (Correa et al., 2006a; Coull et al., 2000; Lange & Röder, 2006; Ramirez et al., 2021), tandis que d'autres ont suggéré qu'elles optimisaient la préparation motrice (Hasbroucq et al., 1999; Korolczuk et al., 2020; Thomaschke et al., 2011; Volberg & Thomaschke, 2017). Dans la suite, nous développons les modèles qui éclairent la composante motrice de notre tâche.

1.5. Les modèles du contrôle moteur

Les modèles du contrôle moteur distinguent le modèle inverse et le modèle 'forward', qui interagissent pour ajuster la planification et l'exécution des mouvements (Flanagan & Wing, 1997; McNamee & Wolpert, 2019; Wolpert et al., 1995; Wolpert & Ghahramani, 2000). Le modèle inverse calcule la commande motrice nécessaire pour atteindre l'état final souhaité et détermine les actions requises pour passer de l'état initial à cet état cible. Une copie de la commande motrice, appelée copie d'efférence, est envoyée au modèle forward. Celui-ci prédit l'état futur du corps et les retours sensoriels associés au mouvement (proprioceptifs, visuels, tactiles) à partir de cette copie. Les prédictions du modèle forward sont ensuite confrontées aux retours sensoriels réellement perçus durant l'exécution du mouvement. La différence entre les prédictions et les perceptions peut générer une erreur de prédiction, qui conduit à un ajustement en temps réel de la commande motrice produite par le modèle inverse. Toutefois, les retours sensoriels nécessaires pour générer cette erreur de prédiction ne sont pas perçus instantanément en raison des délais internes au système, tels que la conduction axonale des récepteurs sensoriels vers le système nerveux central. Par opposition, on retrouve des délais externes

au système, lesquels se réfèrent aux contraintes temporelles imposées par l'environnement. Ces contraintes externes peuvent notamment nécessiter d'exécuter un mouvement en un temps précis. Par exemple, lorsque l'on danse, l'ajustement de ses mouvements au rythme de la musique illustre une contrainte temporelle externe qui influence notre contrôle moteur.

Cela soulève la question des mécanismes qui compensent (1) les délais internes pour synchroniser les retours sensoriels prédits et réels, et (2) les délais externes au système pour assurer une exécution motrice optimale.

1.5.1. Le 'Smith Predictor'

Pour compenser les délais internes, le 'Smith Predictor' a été proposé (Miall et al., 1993; Miall & Wolpert, 1995). Ce modèle utilise deux boucles de rétroaction : la première inclut le modèle forward, précédemment décrit, et la seconde intègre le modèle des délais. Ce dernier ajuste les prédictions du modèle forward en les retardant, pour tenir compte des délais internes au système, et s'assurer de la synchronisation temporelle entre prédictions et retours sensoriels perçus. Les prédictions ajustées sont ensuite comparées aux retours réels grâce à un comparateur qui calcule l'erreur de prédiction. Si les retours sensoriels arrivent plus tard que prévu, une erreur survient. Pour la compenser, des ajustements correctifs en ligne permettent de corriger le décalage.

Pour vérifier l'existence d'un tel mécanisme, des chercheurs ont introduit des délais internes artificiels entre un mouvement et ses retours sensoriels, en imposant par exemple un décalage temporel dans les retours visuels ou proprioceptifs du mouvement (Miall & Jackson, 2006; Rasman et al., 2024). Bien que ces délais artificiels ne correspondent pas aux délais intrinsèques réels du système, ils modifient la temporalité entre le mouvement exécuté et le retour sensoriel. En ce sens, ils sont considérés comme un nouveau délai interne par le système. Les résultats de ces expériences montrent que les participants ajustent progressivement leurs réponses motrices en réponse à ces délais internes artificiels, sans avoir recours systématiquement à des ajustements correctifs en ligne, comme le prédit le modèle du Smith Predictor. Cependant, ces résultats ne permettent pas de déterminer avec précision à quel niveau du contrôle moteur (modèle inverse ou modèle

forward) ces délais internes artificiels sont intégrés pour faciliter un ajustement progressif de la commande motrice.

Un élément de réponse est fourni par les travaux de Rasman et al. (2024). Dans leur expérience, ils ont démontré que l'adaptation aux délais internes artificiels se généralise à différents effecteurs musculaires, allant des muscles de la main aux jambes. Ces résultats sont surprenants, car selon le modèle du Smith Predictor, l'adaptation aux délais internes devrait être spécifique à chaque effecteur. En effet, les délais de transmission axonale varient en fonction de la longueur et de la vitesse de conduction neuronale, comme c'est le cas entre un bras et une jambe. Si l'apprentissage et l'adaptation à ces délais internes artificiels peuvent s'appliquer à plusieurs effecteurs musculaires, cela suggère que la prise en compte des délais internes au système n'est pas limitée à une seule commande motrice, mais pourrait être généralisée à l'ensemble du contrôle moteur.

La question demeure concernant la gestion des délais externes, ceux imposés par l'environnement, qui ne peuvent pas toujours être anticipés avec précision. Par exemple, un joueur de tennis doit frapper la balle au moment opportun tout en s’adaptant aux variations constantes de sa vitesse et de sa trajectoire. Dans ce contexte, il devient difficile de prévoir précisément quand stopper le mouvement, car l'événement extérieur impose sa propre temporalité. La manière dont ces contraintes sont intégrées dans le contrôle moteur reste encore floue. Les modèles inverse et forward pourraient y contribuer : le modèle inverse pourrait intégrer ces contraintes temporelles dans la commande motrice initiale, tandis que le modèle forward ajusterait les prédictions sensorielles en temps réel pour adapter le mouvement aux imprévus de l’environnement.

Cette question revêt un intérêt fondamental et clinique, car y répondre permettrait de mieux caractériser les symptômes moteurs observés dans certaines populations neuro-atypiques, comme celle atteinte de SZ. Ces symptômes ne semblent pas entièrement liés à des altérations dopaminergiques ou à des anomalies neuroanatomiques classiques du système moteur, mais pourraient plutôt, ou aussi, résulter de difficultés à programmer ses actions motrices dans le temps (Giersch et al., 2016). Ces troubles sont décrits dans la suite dans cette introduction.

1.6. Une population neuro-atypique : l'exemple de la schizophrénie

1.6.1. Généralités

La SZ touche environ 1% de la population mondiale (Roy et al., 2021), mais son impact dépasse ce chiffre. La prise en charge des individus atteints inclut des soins médicaux prolongés et un soutien accru des familles. En outre, l'incapacité fréquente des personnes atteintes à maintenir une activité professionnelle limite leur intégration sociale et contribue à leur isolement, ce qui entraîne des répercussions sur leur qualité de vie et sur leur participation active à la société (Charrier et al., 2013). Ces éléments soulignent que les conséquences sociétales de la SZ s'étendent au-delà des 1% individus concernés.

La SZ est une pathologie neurodéveloppementale dont les origines sont multifactorielles et encore mal comprises. Bien que des facteurs de risque génétiques et environnementaux aient été identifiés, leur présence ne permet pas de prédire avec certitude le développement de la maladie ni d'en expliquer pleinement l'étiologie (Abel, 2004; Birnbaum & Weinberger, 2017; Yamada et al., 2019). Le diagnostic de la SZ repose sur l'identification de plusieurs symptômes présents sur une certaine période, principalement détectés à partir des rapports subjectifs des individus en l'absence de biomarqueurs spécifiques. Ces symptômes sont variés et se répartissent en trois grandes catégories (American Psychiatric Association, 2013):

- Symptômes positifs : ces symptômes s'ajoutent au fonctionnement classique de l'individu, et incluent hallucinations et délires.
- Symptômes négatifs : ces symptômes sont retranchés du fonctionnement habituel, et sont souvent associés à une diminution de la motivation, du plaisir, ou de l'expression émotionnelle.
- Symptômes de désorganisation : les symptômes de désorganisation englobent des comportements désorganisés, notamment des troubles de la pensée, du discours, et du comportement moteur.

Dans les symptômes positifs, on retrouve aussi des troubles de l'agentivité qui se manifestent par des délires d'influence où les individus atteints de SZ ont l'impression que leurs pensées ou actions sont influencées ou contrôlées par des forces extérieures.

Certains auteurs ont suggéré que ce type de symptômes pouvait être sous-tendu par un déficit des modèles internes du contrôle moteur (Frith, 2004; Giersch et al., 2016; Haggard et al., 2003).

1.6.2. L'hypothèse de l'altération de la décharge corollaire

Comme décrit dans la section 1.5, les modèles internes du contrôle moteur impliquent une copie d'efférence, c'est-à-dire une copie interne des commandes motrices envoyées aux muscles, pour prédire les conséquences sensorielles du mouvement. Ces prédictions sont comparées aux retours sensoriels réels, et si une différence est détectée, le mouvement est ajusté. Quand les signaux sensoriels perçus correspondent aux prédictions (erreur sensorielle faible ou nulle), ils confirmeraient que l'action a été générée par le sujet qui réalise l'action. Selon Frith (2004) c'est la correspondance entre l'information prédite et réelle qui permet de se sentir auteur de son acte. En outre, cette même correspondance aurait des implications pour le traitement du retour sensoriel. En effet, il n'est pas nécessaire de traiter davantage les signaux qui correspondent aux prédictions, justement parce que ces signaux sont déjà prédits (Shergill et al., 2003). Cette inhibition du retour sensoriel est permise par la décharge corollaire dans les cortex sensoriels. La décharge corollaire informe les systèmes sensoriels des informations attendues (Von Holst & Mittelstaedt, 1950). L'atténuation du retour sensoriel est particulièrement importante dans le cas des sensations auto-générées. Par exemple lorsque nous parlons, la décharge corollaire informe le cortex auditif des sons à venir (Eliades & Wang, 2003; Müller-Preuss & Ploog, 1981). Grâce à ce signal, la réponse sensorielle aux sons auto-générés est atténuée. Cette atténuation empêche une réaction inappropriée à notre propre voix et permet de mieux se concentrer sur les sons externes.

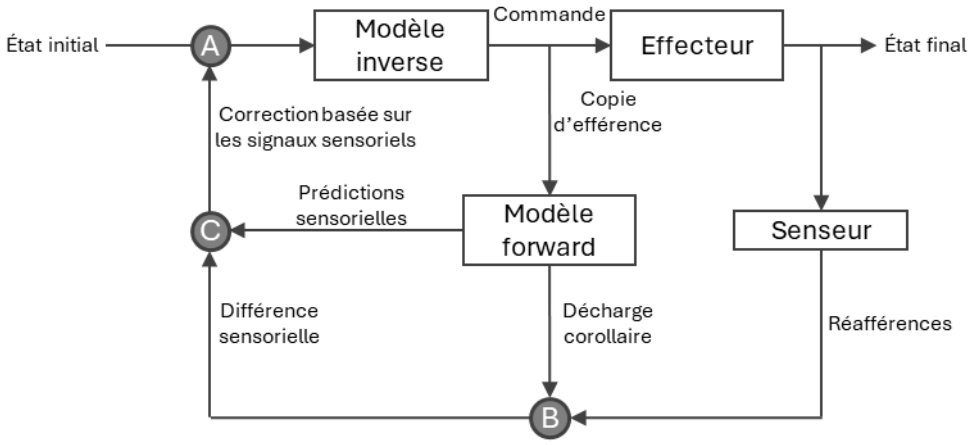

Figure 1. Représentation schématique des modèles de contrôle moteur inverse et prédictif. Le cercle gris (A) représente le point de contrôle moteur où le modèle inverse ajuste sa commande motrice en fonction de l'état initial, actualisé par les informations sensorielles. Le cercle gris (B) constitue le système sensoriel. Enfin, le cercle gris (C) est le contrôleur qui génère l'erreur sensorielle. Figure adaptée de (Winstein et al., 2003).

Dans la SZ, une altération de la décharge corollaire entraînerait une atténuation inadéquate des sensations auto-générées. Ceci pourrait compromettre la perception des actions comme étant auto-initiées et pourrait contribuer aux troubles de l'agentivité (Frith, 2004; Shergill et al., 2005; Wang et al., 2014). Par exemple, lors de la parole, la N1, une composante EEG observée environ 100 ms après un stimulus auditif, est normalement réduite chez les individus neurotypiques, grâce à la décharge corollaire qui permet d'atténuer les sons auto-générés. Chez les individus atteints de SZ, cette réduction de l'onde N1 est beaucoup moins marquée, suggérant un dysfonctionnement de la décharge corollaire (Beño-Ruiz-de-la-Sierra et al., 2024; Ford et al., 2007; Mathalon et al., 2019). En outre, cette altération de la réduction de N1 a été directement corrélée à la sévérité des expériences anormales de soi chez les individus atteints de SZ (Beño-Ruiz-de-la-Sierra et al., 2024). Ces résultats suggèrent que l'altération de la décharge corollaire pourrait contribuer aux troubles de l'agentivité observés dans cette population.

Il reste à déterminer si cette difficulté à supprimer les signaux sensoriels prédits chez les individus atteints de SZ est due à une altération de la décharge corollaire ou à un dysfonctionnement du contrôle moteur en amont de la genèse de la décharge corollaire, lors de la planification motrice.

1.6.3. L’hypothèse d’une planification motrice altérée

Delevoye-Turrell et al. (2006) ont exploré les capacités attentionnelles allouées à la planification et à l’exécution motrice chez des individus atteints de SZ et des neurotypiques en utilisant un paradigme de double tâche. Les participants effectuaient des actions de préhension et de déplacement d’objets en condition de tâche simple ou double. Dans la double tâche, les participants devaient non seulement manipuler un objet, mais aussi réagir à un signal sonore en appuyant sur un interrupteur placé sous leur talon. Les TRs en réponse à ce signal ont été mesurés à trois moments distincts : (1) avant l'initiation du mouvement, permettant d'évaluer le TR lors de la phase de planification, (2) pendant la manipulation de l'objet, ce qui mesurait l'impact du signal sonore sur la performance pendant l'exécution des mouvements, et (3) après que les participants avaient reposé l'objet, pour évaluer les TRs pendant la phase de réinitialisation. En condition de double tâche, le TR des individus atteints de SZ était plus élevé pendant l'exécution que lors de la planification motrice. En revanche, chez les neurotypiques, le TR augmentait davantage lorsque la double tâche intervenait pendant la planification plutôt qu’au cours de l'exécution. Ces résultats suggèrent que chez les neurotypiques la planification motrice requiert de l’attention, tandis que cette phase n’est pas optimale et ne mobilise pas l’attention dans le cas des individus atteints de SZ. D’autres résultats suggèrent également une anomalie de l’allocation de l’attention durant les tâches motrice dans la SZ. En particulier, une sensibilité anormale à des distracteurs a été décrite durant des tâches motrices chez les individus avec SZ (Carment et al., 2019). Les troubles attentionnels sont connus dans la SZ, et pourraient impacter le contrôle moteur. Une alternative (non exclusive) est que les altérations de la programmation motrice requièrent une compensation attentionnelle lors de l’exécution motrice (Delevoye-Turrell et al., 2006).

Une altération spécifique de la programmation motrice a en effet été observée chez les individus atteints de SZ lors de l'exécution de mouvements complexes nécessitant une planification précise. Delevoye-Turrell et al. (2007) ont comparé des individus atteints de SZ à des neurotypiques dans une tâche de pointage du doigt sur une surface. Le mouvement était décomposé en séquences de complexité croissante : une séquence à deux éléments (pointer et lever le doigt), une séquence à trois éléments (atteindre la surface, pointer, et lever le doigt), et une séquence à quatre éléments (atteindre, pointer, lever le doigt, puis stabiliser la main à 30 cm au-dessus de la surface). Le temps de contact du

doigt avec la surface était utilisé comme indicateur de la planification motrice. Une bonne anticipation de ce contact devrait permettre un temps de contact très court, sans attente du retour sensoriel pour effectuer le retrait du doigt. En effet, si l'on attend le retour sensoriel, cela prend au moins 90 ms pour que l'information sensorielle parvienne au cerveau et qu'une commande motrice soit renvoyée en périphérie (Johansson et al., 1992). Toutefois, les individus atteints de SZ ont montré un temps de contact significativement prolongé par rapport aux neurotypiques, avec une augmentation du temps de contact proportionnelle à la complexité des séquences. Ce temps de contact allongé suggère que les individus atteints de SZ attendent le retour sensoriel avant de lever leur doigt, ce qui indiquerait une altération de la planification de la séquence motrice.

Il était possible que le temps de contact prolongé soit dû à une altération des processus de retours sensoriels, ou à un ralentissement non spécifique. Cependant, il a été démontré que les individus atteints de SZ peuvent agripper un objet glissant de façon réflexe aussi vite que les individus neurotypiques (Delevoye-Turrell et al., 2007). Cela indique que l'information sensorielle est utilisée de la même manière chez les individus neurotypiques et atteints de SZ pour adapter leur mouvement. Le déficit observé dans la réalisation de mouvements complexes chez les individus atteints de SZ semble résulter d'une altération des mécanismes de planification de l'action. Planifier une séquence de sous-mouvements pour réaliser un mouvement fluide nécessite d'ordonner chaque étape dans le temps. Les séquences motrices planifiées doivent s'exécuter rapidement et de manière coordonnée, sans dépendre excessivement du retour sensoriel. En revanche, chez les individus atteints de SZ, l'allongement des délais entre les sous-éléments révèle des mouvements fragmentés, moins efficaces. Ces effets pourraient être dus à un défaut de planification temporelle.

1.6.4. Le temps dans la schizophrénie

Dans les tâches d'attente temporelle, certaines études ont montré que les individus atteints de SZ et les neurotypiques obtiennent des résultats similaires, avec un TR plus rapide lorsque la cible survient après un délai long par rapport à un délai court (Ciullo et al., 2018; Martin et al., 2017). Ces résultats suggèrent que ce bénéfice du passage du temps est préservé chez les personnes atteintes de SZ. Cependant, Martin et al. (2017) ont montré que cette préservation n'est pas uniforme dans la SZ : les individus présentant des

troubles du sens de soi ne montrent pas de variation de leur TR en fonction du délai, ce qui indique qu'ils ne bénéficient pas du passage du temps.

Des résultats récents ont suggéré que le bénéfice du passage du temps est plus largement altéré chez les individus atteints de SZ, au niveau du groupe (Foerster & Joos et al., 2024). L'approche a consisté à isoler le bénéfice du passage du temps des effets séquentiels. Nous avons vu que le délai de l'essai précédent influence le TR de l'essai actuel, indépendamment du bénéfice du passage du temps (Vallesi & Shallice, 2007) : les TRs au délai court sont ralentis lorsque le délai précédent était long (séquence long-court), par rapport à des essais où le délai précédent était également court (séquence court-court). Dans une distribution où 50% des essais ont un délai court et 50% ont un délai long, la moitié des essais avec un délai court est précédée d'un délai long. Ainsi, environ 50% des TRs au délai court seront ralentis en raison des effets séquentiels. Les effets séquentiels ne sont pas perturbés chez les individus atteints de SZ (Foerster & Joos et al., 2024), et peuvent annuler l'altération de l'effet du passage du temps.

Pour isoler l'effet du passage du temps sur les TRs, il est nécessaire de dissocier cet effet des effets séquentiels. La méthode proposée par Foerster et Joos et al. (2024) consiste à analyser uniquement les essais précédés d'un essai avec un délai identique, en comparant spécifiquement les séquences d'essais court-court et long-long. En appliquant cette méthode, les auteurs ont démontré que chez les individus atteints de SZ, le bénéfice du passage du temps sur les TRs n'était pas préservé. Contrairement aux individus neurotypiques, les individus atteints de SZ ne montrent pas de TR plus rapide lorsque la cible survient après un délai long comparé à un délai court. Ces résultats comportementaux suggèrent que les capacités de prédiction temporelle sont altérées dans la SZ. Ces résultats sont cohérents avec les données EEG, qui montrent une réduction de l'amplitude de la CNV chez les individus atteints de SZ par rapport aux individus neurotypiques (Ford et al., 2010; Osborne et al., 2020).

Cette thèse est la continuation de ces travaux et consistait initialement à développer un protocole permettant de sensibiliser la mesure des altérations des capacités de prédiction temporelle en lien avec le sens de soi. En effet, Martin et al. (2017) avaient déjà établi, dans le cadre d'un protocole de tâche d'attente temporelle, une corrélation entre les altérations du bénéfice du passage du temps et celles du sens de soi, évalué cliniquement.

Pour rendre notre tâche plus sensible aux troubles du sens de soi, nous avons choisi d'utiliser des stimuli tactiles. La modalité tactile est particulièrement pertinente pour l'étude du sens de soi, et plus spécifiquement du soi corporel, altéré dans la SZ (Ferri et al., 2014; Thakkar et al., 2011).

Nous avons également proposé d'inclure une composante motrice pendant l'attente de la cible. Cette composante devait également sensibiliser notre mesure aux troubles du sens de soi corporel. Le lien entre le soi corporel et la motricité est manifeste ; nos mouvements contribuent à notre perception d'être les auteurs de nos actions, un aspect central du soi corporel (Gallagher, 2000), souvent altéré dans la SZ (Frith, 2004; Giersch, 2018). De plus, le mouvement génère des retours sensoriels dits ‘haptiques’, englobant les informations tactiles et proprioceptives associées à nos actions. Cette perception haptique est essentielle à la construction d’un sens de soi corporel cohérent (Foerster et al., 2021).

1.7. Objectifs de la thèse :

Cette thèse s'est concentrée sur le développement et l'application de nouvelles tâches d’attente temporelle. Compte tenu de la dimension méthodologique de ce travail, il est essentiel de résumer brièvement en quoi consistent ces tâches afin de mieux comprendre les objectifs des études menées.

Nous avons conçu un protocole d'attente temporelle où les participants devaient effectuer un mouvement continu pendant la période d’attente. Concrètement, l’index de leur main dominante était posé sur une surface plane, et ils devaient débuter un mouvement linéaire sur cette surface dès qu’une vibration tactile était ressentie au coude (signal de départ). La consigne qui leur était donnée était de poursuivre ce mouvement jusqu’à ce qu’une vibration tactile soit ressentie après un délai court ou long au poignet cette fois (signal cible). Lorsque le signal cible était ressenti, les participants devaient stopper le plus rapidement possible leur mouvement. Les mouvements étaient effectués à l'intérieur d'une boîte fermée pour éviter que les participants ne puissent voir leur main.

Initialement, nous avons utilisé une tâche au cours de laquelle les participants changeaient de direction à chaque essai. Nous avons mesuré le temps qu’ils mettaient pour arrêter leur mouvement, ce qui constituait leur TR, un indicateur classique d'exécution de la réponse

utilisé dans la littérature des tâches d'attente temporelle. Nous avons vérifié, sur une cohorte de volontaires sains, si nous pouvions observer les indicateurs des capacités de prédiction temporelle, typiquement rapportés dans la littérature sur les tâches d'attente temporelle, en ce qui concerne les TRs dans notre protocole. Nous avons constaté le bénéfice du passage du temps : les participants réussissaient à arrêter leur mouvement plus rapidement lorsque le signal cible survenait après un délai long plutôt qu'après un délai court. Cependant, à notre grande surprise, nous n'avons observé aucun effet séquentiel sur les TRs. Pour rappel, le moment où le signal cible survient lors de l'essai précédent devrait influencer la prédiction de son occurrence à l'essai suivant. Par exemple, après un essai où l'arrêt a eu lieu au délai long, le mouvement suivant devrait être préparé pour un arrêt au délai long. En cas d'arrêt au délai court, l'arrêt devrait être moins efficace. Pourtant, nous avons observé que, au délai court, l'efficacité de l'arrêt était similaire, que le délai précédent ait été court ou long.

Nous avons formulé l'hypothèse selon laquelle l'absence d'effets séquentiels est liée au changement de direction entre les essais. Le changement de direction implique un changement de commande motrice d'un essai à l'autre, puisque déplacer son bras vers l'avant ou vers l'arrière sollicite les muscles et articulations différemment. Comme nous l'avons discuté dans la section 1.5 sur le contrôle moteur, le modèle inverse est celui qui établit les commandes motrices (Wolpert & Ghahramani, 2000; Wolpert & Kawato, 1998). Si la prédiction temporelle s'intègre à ce modèle, elle est alors associée à une commande motrice spécifique. Dans ce cas, la prédiction du moment d'occurrence du signal cible, fondée sur son occurrence à l'essai précédent, serait intrinsèquement liée à un mouvement particulier. Lorsque la commande motrice change, il devient alors difficile de transférer cette prédiction à l'essai suivant.

Pour valider notre raisonnement, nous avons conçu une tâche où le mouvement serait répété dans la même direction à chaque essai. Si des effets séquentiels réapparaissaient sur les TRs dans cette tâche, cela indiquerait que le changement de direction était probablement la cause de l'absence d'effets séquentiels dans la tâche initiale. C'est ainsi que ces résultats préliminaires ont mené à la question de l'intégration de la prédiction motrice dans le programme moteur.

Deux tâches ont été utilisées :

- La tâche unidirectionnelle : après l'arrêt du mouvement, les participants revenaient systématiquement à leur position de départ, et devaient attendre le prochain signal de départ pour débuter leur nouveau mouvement. Cette consigne permettait aux participants d'effectuer les mouvements dans la même direction à chaque essai.
- La tâche multidirectionnelle : après l'arrêt, les participants restaient immobiles et attendaient le prochain signal de départ pour effectuer un nouveau mouvement, dans une direction différente du précédent. Par exemple, s'ils s'étaient déplacés vers la droite lors de l'essai précédent, à l'essai suivant ils pouvaient aller dans une des trois directions suivantes : la gauche, l'avant ou l'arrière.

En plus des TRs, nous avons recueilli des indicateurs cinématiques tout au long de la trajectoire. Nous avons en particulier déterminé le moment où la vitesse du mouvement commence à ralentir, ce qui reflète la préparation à l'arrêt (Woodworth, 1899). Un mouvement n'est jamais programmé pour durer indéfiniment ; l'arrêt du mouvement fait partie intégrante du programme moteur. Cependant, dans nos tâches, l'arrêt est déclenché par l'occurrence d'un signal cible, dont le moment peut être anticipé. Cette anticipation devrait influencer la cinématique du mouvement en permettant un ralentissement de l'action pour préparer son arrêt. En effet, le plus souvent le mouvement mène au contact avec une surface, et il faut éviter une collision brutale avec la surface. Ce risque explique l'importance et l'automaticité du ralentissement de l'action en amont de son arrêt. La question centrale de nos nouvelles tâches expérimentales est donc de comprendre comment la prédiction temporelle influence à la fois la préparation de l'arrêt et l'arrêt lui-même, un aspect qui n'est pas clairement établi dans les modèles classiques de contrôle moteur.

Nous avons examiné les effets séquentiels sur les indicateurs de préparation (indicateurs cinématiques) et d'exécution (TR) de l'arrêt recueillis dans nos tâches expérimentales, afin de vérifier l'absence d'effets séquentiels dans la tâche multidirectionnelle, et sa restauration dans la tâche unidirectionnelle.

L'objectif de l'étude 1 était de comprendre comment la prédiction temporelle s'intègre dans le contrôle moteur chez une population neurotypique, avant de l'appliquer à des populations neuro-atypiques.

Nos résultats ont révélé une double prédiction temporelle à la même échelle temporelle. D'une part, nous avons observé une prédiction temporelle liée à la commande motrice, mise en évidence par les effets séquentiels sur nos indicateurs comportementaux sélectivement dans la tâche unidirectionnelle. D'autre part, une prédiction temporelle indépendante du mouvement spécifique a été observée, avec des effets séquentiels observés à l'EEG dans les deux tâches expérimentales (Arrouet et al., 2024, *révision soumise à NeuroImage*).

La caractérisation d'une prédiction temporelle liée à la commande motrice soulève des questions sur son développement au cours de la vie. Dans les tâches classiques d'attente temporelle, les adultes montrent des TRs plus rapides et des réponses plus précises que les jeunes individus, suggérant des mécanismes de contrôle moteur qui se perfectionnent avec l'âge (Adams & Lambos, 1986; Eckert & Eichorn, 1977; Johnson et al., 2015). Bien que les jeunes et les adultes bénéficient d'une manière similaire du passage du temps pour préparer leur réponse à un stimulus prédictible (Droit-Volet & Coull, 2016), la façon dont ces mécanismes de prédiction temporelle sont liés à la préparation motrice pourrait différer et être plus efficace chez les adultes (Mento & Tarantino, 2015; Vallesi & Shallice, 2007).

L'objectif de l'étude 2 était de comprendre comment les capacités de prédiction temporelle associées à une action motrice évoluent avec l'âge.

Nous avons comparé les performances de participants neurotypiques âgés de 9 à 24 ans et observé des effets séquentiels sur les indicateurs cinématiques des trajectoires, indépendamment de l'âge, suggérant que la prédiction temporelle motrice est déjà présente à 9 ans. En revanche, des effets séquentiels ont été observés sur les TRs dans les deux tâches expérimentales, contrairement à la première étude. Ces effets séquentiels sur le TR pourraient refléter des processus de préparation motrice (arrêt) et sensorielle (prédiction du signal cible). Dans la tâche multidirectionnelle, la commande motrice change. La prédiction temporelle du signal cible n'est donc pas associée à un mouvement spécifique. La présence d'effets séquentiels sur la réponse dans la tache multidirectionnelle montre donc une influence dissociée du programme moteur. Cela suggère que l'intégration sensorimotrice n'est pas encore pleinement établie avant l'âge

adulte, ce qui pourrait expliquer l'amélioration des performances dans ce type de tâche avec l'âge (Arrouet et al., 2024, *en préparation*).

Dans les études 3 et 4 de cette thèse, nous avons exploré les troubles de la prédiction temporelle en populations neuro-atypiques afin de mieux comprendre ces dysfonctionnements en condition pathologique.

L'étude 3 avait pour objectif d'examiner si la prédiction temporelle associée à une action motrice, présente chez les adolescents neurotypiques, était altérée chez des enfants et des adolescents à HR de conversion psychotique. Par ailleurs, elle avait pour objectif de vérifier si la maturation des processus d'intégration sensorimotrice différait selon les populations expérimentales.

Chez les individus à HR, les effets séquentiels dans la tâche multidirectionnelle étaient plus marqués par rapport aux neurotypiques, tant sur les TR que sur les indicateurs cinématiques. Pour rappel, des effets séquentiels dans cette tâche sont synonymes d'une intégration sensorimotrice imprécise. Cette différence pourrait indiquer que les processus d'intégration sensorimotrice chez les individus à HR sont moins matures que chez leurs pairs neurotypiques. De plus, des effets séquentiels ont été observés même au délai long. Entre le délai court et avant l'occurrence du signal cible au délai long, la préparation de l'arrêt devrait être optimisée, indépendamment du délai de l'essai précédent. Nous suggérons que la prédiction sensorielle chez les individus à HR est plus dissociée du programme moteur par rapport aux neurotypiques, soulignant ainsi une immaturité plus prononcée des processus sensorimoteurs (Arrouet et al., 2024, *en préparation*).

L'étude 4 visait à examiner les processus de prédiction temporelle liés à une action motrice chez des individus atteints de SZ de manière chronique.

Les résultats préliminaires n'ont pas permis d'explorer les indicateurs cinématiques de la trajectoire ni les effets séquentiels. Cependant, les performances comportementales et les réponses EEG ont montré que les individus atteints de SZ bénéficiaient du passage du temps de manière similaire aux neurotypiques dans nos tâches motrices. Ces résultats suggèrent que la réalisation d'un mouvement continu pendant la période d'attente pourrait rétablir le bénéfice du passage du temps chez cette population.

2. MATÉRIELS ET MÉTHODES

2.1. Participants

Les caractéristiques démographiques des participants de chaque étude sont résumées dans le tableau 1. Dans l'étude 4, six participants (sur sept) de chaque groupe sont appariés selon le sexe, l'âge, et le niveau d'études avec un participant du groupe opposé.

Etudes	Population	Nombre	Sexe H/F	Latéralité droite/gauche	Age	Années d'études
1	Neurotypiques	25	6/19	23/2	22.7 ± 3.4	15.1 ± 1.6
2	Neurotypiques 9 – 12 ans	10	3/7	9/1	10.5 ± 1.4	5.4 ± 1.5
	Neurotypiques 13 – 17 ans	13	6/7	12/1	14.8 ± 1.5	9.5 ± 1.5
	Neurotypiques 18 – 24 ans	12	3/9	11/1	21.9 ± 2.1	16.0 ± 2.0
3	Individus à HR 9 – 12 ans	9	3/6	8/1	11.2 ± 0.8	5.8 ± 0.8
	Individus à HR 13 – 17 ans	15	8/7	13/2	14.4 ± 1.2	8.5 ± 1.1
4	Neurotypiques	8	7/1	8/0	41.2 ± 11.0	12.8 ± 3.0
	Individus atteints de SZ	7	6/1	7/0	44.8 ± 10.8	10.3 ± 2.0

Tableau 1. Caractéristiques démographiques des participants de chaque étude. L'âge et les années d'études sont donnés en moyenne ± écart-type. Abréviations : H : homme, F : femme, HR : haut-risque génétique de conversion psychotique, SZ : schizophrénie.

Tous les participants (et leur représentant légal pour les individus mineurs) ont donné un consentement écrit libre et éclairé. Chaque étude a fait l'objet d'une approbation du comité éthique local, conformément à la Déclaration d'Helsinki.

2.2. Équipement

Chaque étude s'est déroulée dans une pièce sombre et silencieuse.

Deux moteurs vibro-tactiles Precision Micro-Drives© délivraient les stimuli tactiles et étaient fixés sur l'avant-bras dominant des participants : l'un sous le coude pour le premier stimulus (signal de départ), et l'autre au poignet (signal cible) auquel il fallait réagir. Les moteurs étaient connectés à un boîtier de stimulation Chronos E-Prime 3.0. L'intensité des vibrations était fixée à 3.0 V, soit une fréquence de 230 Hz. En fonction des études, les participants portaient des bouchons d'oreilles en caoutchouc ou un casque pour éviter d'entendre le bruit des vibrations.

Les tâches étaient contrôlées par un ordinateur et programmées sur E-Prime 3.0.

2.2.1. Tâches motrices

Les participants étaient assis face à une boîte. Avant le début du protocole, les participants pouvaient vérifier que l'intérieur de la boîte était vide. Ils devaient ensuite placer leur main dominante à l'intérieur de la boîte, le poing fermé et l'index tendu. Puis, la boîte était recouverte d'un épais tissu noir pour empêcher toute visibilité à l'intérieur et bloquer l'entrée de lumière.

Les mouvements linéaires de l'index des participants étaient enregistrés à l'aide d'une LED rouge fixée à l'ongle de l'index, et filmés par une caméra GoPro HERO7. La caméra, positionnée à une hauteur suffisante pour capturer toute la boîte, enregistrait en champ de vision linéaire, avec une résolution de 120 Hz et en format HD intégral 16:9.

2.2.2. Tâche contrôle

Dans cette tâche, les participants étaient assis face au boîtier de stimulation Chronos E-Prime 3.0.

2.3. Procédure

Avant chaque tâche, les participants réalisaient quelques essais d'entraînement, dont le nombre variait selon les études considérées. Cette phase d'entraînement permettait à l'expérimentatrice de vérifier que les consignes de chaque tâche étaient bien comprises par les participants.

Pour maintenir l'imprévisibilité du début de chaque nouvel essai, un intervalle inter-essai variable (ITI) était utilisé. Le nombre total d'essais et les ITI seront précisés pour chaque étude.

2.3.1. Tâches motrices

Dans les tâches d'intérêt, dites 'tâches motrices' dans la suite du texte, les participants devaient effectuer un mouvement linéaire avec l'index de leur main dominante au contact d'une surface. Cette surface était située à l'intérieur de la boîte. Ils devaient débuter leur mouvement à la suite d'une vibration tactile de 100 ms appliquée sous le coude (signal de départ) et arrêter ce mouvement le plus rapidement possible à la suite d'une vibration tactile de 100 ms appliquée au poignet (signal cible). Le signal cible survenait après un délai de 1000 ms (court) ou de 1700 ms (long).

Les deux tâches motrices différaient principalement par le type de mouvement effectué (Figure 2). Dans la tâche dite 'multidirectionnelle' dans la suite du texte, les participants devaient changer la direction de leur mouvement à chaque essai, comme ils l'auraient fait s'ils devaient explorer un labyrinthe (Figure 2). Les mouvements étaient restreints aux axes X et Y : ils devaient être effectués au contact de la surface dans la boîte, en allant à droite, à gauche, vers l'avant ou vers l'arrière (toujours en ligne droite). Les diagonales n'étaient pas permises. Dans la tâche dite 'unidirectionnelle' dans la suite du texte, les participants devaient revenir à la même position avant le début de l'essai suivant, de manière à aller dans la même direction à chaque essai (Figure 2).

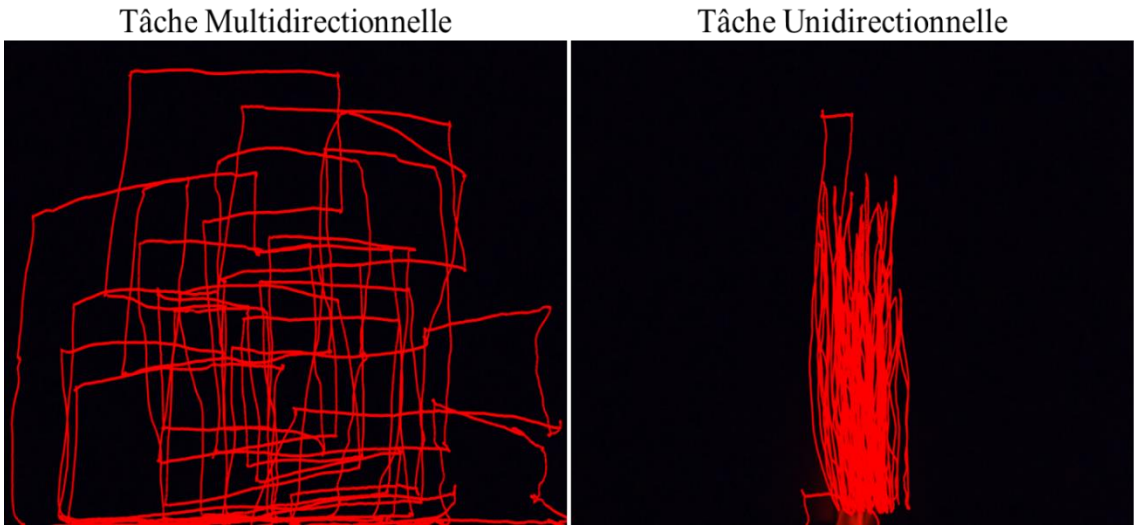

Figure 2. Images des trajectoires de l'index d'un participant, réalisées sur la surface à l'intérieur de la boîte, dans les tâches multidirectionnelle et unidirectionnelle. Le tracé rouge, représentant la lumière de la LED filmée, permet de reconstruire toutes les trajectoires empruntées par le participant. Chaque trait correspond à un essai. La différence entre les tâches est claire : dans la tâche multidirectionnelle, la direction change à chaque essai, tandis que dans la tâche unidirectionnelle, le participant revient approximativement à la position de départ avant le début du prochain essai, et va toujours dans la même direction à l'essai suivant.

2.3.2. Tâche contrôle

Dans la tâche contrôle, l'équipement et les stimuli étaient identiques à ceux des tâches motrices. Seule la manière dont les participants répondaient au signal cible était différente.

Dans cette tâche contrôle, la vibration appliquée sous le coude servait à avertir le participant que l'essai avait débuté, et que la vibration appliquée au poignet (signal cible) allait arriver. Les participants devaient réagir aussi rapidement que possible à l'occurrence du signal cible en appuyant avec leur main dominante sur le bouton central du boîtier de stimulation Chronos E-Prime 3.0.

Cette tâche est plus proche des expériences utilisées dans la littérature, même si celles-ci utilisent plus souvent des stimuli auditifs ou visuels (Droit-Volet & Coull, 2016; Johnson et al., 2015; Martin et al., 2017; Mento, 2017). Cette tâche contrôle nous a permis de

vérifier que les performances de nos participants correspondaient aux résultats de la littérature pour le type de population considérée dans un protocole d'attente temporelle classique.

2.4. Analyses des données

2.4.1. Tâches motrices

Dans nos deux tâches motrices, nous avons enregistré les trajectoires et recueilli nos indicateurs comportementaux à partir des images vidéo collectées avec la caméra GoPro, importées sous le format '.MP4' dans MATLAB 2021b.

Nos vidéos ont été segmentées en essais de 3000 ms chacun. Le début de chaque essai était marqué par l'occurrence du signal de départ. Cette vibration était signalée par une LED bleue à l'intérieur de la boîte, qui s'allumait au début du signal de départ et restait allumée pendant 100 ms, couvrant toute la durée de la vibration. De même, lorsque le signal cible survenait, une LED verte s'allumait à l'intérieur de la boîte et restait allumée pendant toute la durée de cette vibration.

Nous avons analysé les trajectoires du doigt (c'est-à-dire de la LED) avec MATLAB. Nous avons établi plusieurs critères pour permettre au script d'identifier les latences d'arrêts ou TRs définis ci-après. Les critères sont décrits en détail dans le manuscrit principal de l'étude 1 (chapitre 3 page 30).

2.4.1.1. Latence d'arrêt ou TR

Nous avons mesuré les latences d'arrêt des participants, c'est-à-dire le délai nécessaire pour arrêter le mouvement après l'occurrence du signal cible. Cette latence d'arrêt était utilisée comme TR dans notre protocole. Le TR est l'indicateur le plus fréquemment utilisé pour évaluer les performances des participants dans les tâches d'attente temporelle. Ce TR nous a permis d'extrapoler les indicateurs comportementaux typiques des capacités de prédiction temporelle (c'est-à-dire, bénéfice du passage du temps et effets séquentiels) dans nos deux tâches motrices.

Le TR a été défini comme l'intervalle entre l'occurrence du signal cible et le moment où le mouvement du participant était considéré comme arrêté. Puisque les TRs ont été extraits à partir d'images vidéo dans les deux tâches motrices, des critères spécifiques ont été établis afin que les programmes d'analyse identifient précisément le moment d'arrêt. Ces critères sont décrits dans le manuscrit principal de l'étude 1 (chapitre 3 page 30). Chaque point d'arrêt détecté a ensuite été inspecté visuellement, participant par participant et essai par essai, pour vérifier la cohérence des critères appliqués et confirmer la validité de la détection automatisée. Le point d'arrêt était défini comme le premier moment où tous nos critères étaient satisfaits.

Si aucun point ne répondait à ces critères, il était considéré que le participant ne s'était pas arrêté (erreur d'omission) et l'essai était exclu des analyses ultérieures. De plus, si le mouvement était arrêté avant ou moins de 150 ms après le signal cible, cet arrêt était considéré comme anticipé et l'essai était également exclu des analyses (Jana et al., 2020). Il est important de préciser que les essais exclus pour arrêt anticipé incluaient également ceux où les participants entraient en collision avec les parois de la boîte durant leur trajectoire. Bien que rare, ce type de collision entraînait un arrêt du mouvement avant le signal cible. Dans ces cas, la consigne donnée était de rester immobile jusqu'au signal cible dans la tâche unidirectionnelle, puis de revenir à la position de départ avant le prochain essai, ou de rester immobile jusqu'à l'occurrence du prochain signal de départ dans la tâche multidirectionnelle.

2.4.1.2. Points de décélération

Ralentir son mouvement en anticipation de sa fin est caractéristique de la cinématique du mouvement. Ce ralentissement reflète le moment et la manière dont la fin du mouvement est anticipée par le programme moteur (Duque et al., 2017; Woodworth, 1899). Le début de ce ralentissement est utilisé comme indicateur du moment où la préparation à l'arrêt commence, que nous désignerons par la suite comme le 'point de décélération'. Dans chaque tâche motrice, deux délais sont présents, ce qui nous a amenés à considérer deux points de décélération : le premier, qui se situe avant l'occurrence du signal cible à 1000 ms (délai court), et que nous appellerons le 'premier point de décélération', et le second, qui se situe entre 1000 ms et 1700 ms dans les essais avec un délai long, que nous désignerons comme le 'deuxième point de décélération'. Avant 1000 ms, les participants

ne savaient pas si le signal cible surviendrait au délai court ou au délai long, ce qui justifie l'analyse d'un premier point de décélération dans tous les essais, indépendamment du délai.

Les critères utilisés pour identifier les points de décélération étaient identiques, à l'exception de la fenêtre d'intérêt dans laquelle nous les avons définis. Ces critères sont décrits en détail dans le manuscrit principal de l'étude 1 (chapitre 3, page 30). Tout comme pour les points d'arrêt, les points de décélération ont été définis comme les premiers ralentissements répondant à l'ensemble de nos critères.

2.4.2. Tâche contrôle

Dans la tâche contrôle, les essais correspondant à des omissions (i.e. aucune réponse donnée par le participant), des réponses incorrectes (i.e. appuyer sur le mauvais bouton) et des réponses anticipées (i.e. une réponse donnée avant ou moins de 150 ms après le début de la vibration au poignet) ont été exclus des analyses.

CHAPITRE 3. TASK-SPECIFIC TEMPORAL PREDICTION MECHANISMS REVEALED BY MOTOR AND ELECTROENCEPHALOGRAPHIC INDICATORS

Arrouet, A., Marques-Carneiro, E., Marquet, P., Giersch, A., (révision soumise à NeuroImage). Task-Specific Temporal Prediction Mechanisms Revealed by Motor and Electroencephalographic Indicators.

3.1. Main Manuscript

Highlights

- Different mechanisms of temporal prediction coexist on the same temporal scale.
- One temporal prediction is intrinsically linked to the motor movement.
- EEG-visible temporal preparation is not intrinsically linked to motor movement.
- Temporal prediction affects movement execution more than its initiation

Abstract

Time prediction is pervasive, and it is unclear whether it is supra-modal or task-specific. This study aimed to investigate the role of motor temporal prediction in preparing to stop a movement following a sensory stimulus. Participants performed a straight-line movement with their finger until a target signal, which occurred after a short or long foreperiod. In one task, participants changed movement direction between trials (multidirectional task), while in the other, they always moved in the same direction (unidirectional task). The motor trajectory and EEG signals were continuously recorded. During the foreperiod, participants slowed down their movement, reflecting preparation to stop. To assess the influence of motor temporal prediction we examined how a given trial influences performance on the subsequent trial (sequential effect) when the movement changes or stays the same (multi- vs. unidirectional). In the unidirectional task, but not in the multidirectional task we found sequential effects on several behavioural parameters. In contrast, sequential effects were observed in both tasks on EEG results. This study revealed a temporal prediction related to motor movement (behavioural indicators), and a temporal preparation while waiting for the target (EEG indicator). These findings highlight the importance of considering various temporal prediction mechanisms.

Keywords: Temporal predictions; Motor; Perception; Sequential effects; Contingent negative variation

1. Introduction

Timing is ubiquitous in the brain, and there is no dedicated area for time. Performing a motor action requires planning motor elements in time and processing sensory feedback at the right time. Such timing activities require the cerebellum, the supplementary motor area, the parietal and prefrontal cortices (Coull & Giersch, 2022), i.e. areas also involved in other mental activities. This makes it difficult to understand how time intervenes in the different functions of our every day life. This is the case for motor control, which requires a high level of temporal precision. To achieve optimal motor control when learning a motor skill, we may repeat the same movement over and over. Repetition on a trial-to-trial basis has been shown to enhance performance on a short-term scale (Bertelson, 1961; Vleugels et al., 2020). It may be useful especially when playing music or dancing, where the timing of the movement is critical (Levitin et al., 2018). In such conditions, previous experience may help to execute a movement in the required time. However, the same movement in real life can be done while our body position changes, or the environmental conditions change. For example, a violinist may play the same note by moving the bow from right to left or from left to right. Skilled performers are supposed to be efficient even in altered conditions (Johnson, 1961; Ranganathan et al., 2020), meaning they can execute their action efficiently even when the action has to be adjusted to external conditions, such as a different body position, or the use of a new instrument. The question is: when the motor program changes, is it still possible to use the temporal information from past experiences?

The question is not trivial, inasmuch previous studies suggested that past time experience has strong influences on the current time expectations, whether tested with simple or choice reaction time (RT) tasks (Bertelson & Boons, 1960; Los et al., 2014; Salet et al., 2022; Steinborn et al., 2008). The strength of these effects may give the impression that they are ubiquitous. Whether the influence of past time experience generalizes to the case where the movement changes remains nonetheless an open question. The response to that question may depend on the extent to which time prediction mechanisms are integral to movement planning. Biomechanical, internal constraints can be expected to be integral to the movement (Miall et al., 1993; Rasman et al., 2024). In contrast, if the movement must be completed in e.g. 1.2 seconds to play a specific musical note, this is an external

constraint, not a biomechanical one. The external constraint may or may not be integrated in the motor program itself. It might be processed independently and only coupled with the motor program. If at least part of the temporal prediction is integral to the motor program, it should be difficult to re-use this prediction when the movement requires a different motor program. For example, if the movement changes direction, different muscles are involved, with a different sequence, and potentially a different timing of muscle contraction (Miall et al., 1993). This should be the case even if the external constraint remains the same, i.e. if the movement should be finished at the same time. In this study, we gather behavioural and electroencephalographic (EEG) indicators during the expectancy period (rather than after) preceding the stopping of a movement, and we compare these indicators when the movement is repeated or changed from trial-to-trial.
The investigation of temporal prediction abilities is based on the widely used variable foreperiod paradigm, where a first stimulus indicates the start of the trial, followed at a short or a long foreperiod by a target. It is well established in the literature that the later the target is presented, the faster the participant will react to it (Coull, 2009; Martin et al., 2017; Niemi & Näätänen, 1981; Nobre et al., 2007; Woodrow, 1914). According to hazard-based theories, the 'variable foreperiod effect' can be explained as follows: as time passes, the probability of the target appearing increases, and the benefit of the passage of time allows for a higher level of readiness. Alternatively, the formalized Multiple Trace Theory of Temporal Preparation (fMTP) suggests that temporal preparation in variable foreperiod paradigm is shaped by memory traces of previous trials, with past experiences optimizing the motor system readiness (Los et al., 2017; Salet et al., 2022). A discussion regarding these models is beyond the aim of our manuscript, but the latter interestingly considers the role of the motor system.

Many authors raised the question of whether improved performance in variable foreperiod paradigms (faster RTs and higher accuracy) was due to facilitated perceptual processes and/or to an enhanced motor preparation in response to the target. Temporal expectations have been found to enhance the reaction to predictable targets over time (Correa et al., 2005; Correa et al., 2006a; Lange & Röder, 2006; Ramirez et al., 2021) and some experiments emphasize the role of motor preparation in temporal expectation (Thomaschke & Dreisbach, 2013; Volberg & Thomaschke, 2017). To demonstrate the association between temporal preparation and motor readiness, Thomaschke et al. (2011) used a speeded choice RT where participants responded to a target using either the left or

right hand. The authors manipulated contingencies between foreperiods and either stimulus features (shape) or responses (right or left). For example, a specific shape was more frequently associated with a given foreperiod. Thomaschke et al. (2011) observed the typical benefits of temporal predictability on performance only when foreperiods were linked to response sides, not to shapes. However, it is questionable to what extent RT are enough to quantify in equal measure the advantage provided by motor versus perceptual temporal prediction, inasmuch RT is inherently associated with a motor response. It may have limited the chance of seeing any foreperiod effect in the case of a shape contingency. It is the limitations in the use of RT that led us to adapt the variable foreperiod task to introduce a motor component and to answer our question. As a reminder, we wish to know to which extent the temporal prediction associated with a motor action is independent of the motor program. In the present study, we created two distinct motor tasks. Concretely, we instructed participants to perform a straight-line movement. They initiated the movement after a first tactile stimulus (which we will name the 'start signal' in the remainder of the text) and stopped it as fast as possible after a second tactile stimulus (which we will call the 'target signal' in the remainder of the text). It should be noted that this procedure differs from the stop signal procedure, whose aim it is to explore how the initiation of a task can be stopped, or not, depending on the occurrence of a stop signal (Logan & Cowan, 1984). In our task, participants were asked to halt a movement in all trials, unlike the stop signal approach, which focuses on how movement or thought execution can be prevented in a minority of trials by a signal that comes as a rare event. Additionally, in our protocol participants had no other task than stopping their movement after the target signal. To avoid any confusion with the stop signal procedure, we named our signals according to the variable foreperiod literature.

In the present study we chose to use a motor action to access the motor kinematics parameters reflecting motor preparation. We also devised two different tasks with vs. without a change in movement, to test the idea of a temporal prediction attached to the motor program. In one task participants moved in the same direction on each trial; in the other participants changed the direction of their movement from one trial to the next. Repeating a movement allows to rely on the temporal information specifically attached to the previous movement. How much the temporal information is attached to the motor program is explored by manipulating the delay between the start signal and target signal. The task includes two conditions: in one, the action has to be stopped after a short

foreperiod; in the other, it has to be stopped after a long foreperiod. This means that there is no trivial repetition of a strictly identical movement. Instead, the movement can be short or long. In case of an additional change in the movement direction, there is also a change in the internal biomechanical constraints that affect the time needed to achieve the movement. Those constraints are known to the system, and the movement can be adapted accordingly. For example, the model of motor control proposed by Miall et al. (1993) includes a Smith Predictor, which generates specific predictions in order to anticipate delays that are inherent to the motor system. The Smith Predictor may thus help to adjust the motor program in order to realize the action in the expected time (Rasman et al., 2024).

However, usual models of motor control distinguish between the feed-forward inverse model, which helps to build a motor program before movement execution, and the forward model, which predicts the sensory consequences of the action (Wolpert & Kawato, 1998). Some studies (Miall & Jackson, 2006) have suggested that changes in the sensory feedbacks might not necessarily reflect in the motor program itself, but whether or not this applies to time prediction is unclear. In our task, time expectation regarding the target signal should affect the movement kinematics by indicating when to slow down in anticipation of the target signal. This motor preparation should speed up the movement stop. According to hazard-based models, and since the probability of the target signal is 50% at short foreperiod and 100% at long foreperiod, preparation should be optimal only at long foreperiod, resulting in the usual variable foreperiod effect on the motor stop (Correa et al., 2006a; Martin et al., 2017; Niemi & Näätänen, 1981). From the standpoint of the fMTP, memory traces from previous trials lead to gradual motor preparation, allowing for a more efficient motor reaction at long foreperiods (Los et al., 2017; Salet et al., 2022). Both models predict faster motor times at long foreperiods. This may occur whether the expectation is integral to the feed-forward inverse program or only used to adjust the reaction to the target signal with the forward model. Our point is that if the feed-forward program includes the time prediction, it may be difficult to transfer this prediction from one action to the following one, when the movement changes. We investigate this by exploring trial-to-trial effects in the variable foreperiod paradigm.

In the typical variable foreperiod task, the influence of recent temporal experience on current temporal expectation has been well described. Such ‘sequential effects’ are as follows: with a short current foreperiod, RT tends to be longer if the preceding foreperiod was long compared to when it was short. In contrast, when the current foreperiod is long,

the preceding foreperiod has no effect on RT (Los, 2010; Niemi & Näätänen, 1981; Woodrow, 1914; Zahn et al., 1963). Various mechanisms could underlie sequential effects. The hazard-based theories cannot directly account for such effects, but dual-process models (Vallesi et al., 2007) assume a mechanism that is distinct from the one originating the variable foreperiod effect, and is based on the automatic prediction that two consecutive trials will be similar. When two short foreperiods occur in succession, this corresponds to the expectation, whereas if a short foreperiod follows a long one, participants are not prepared to respond because they expected another long foreperiod. This surprise effect results in slower RTs in the long-short trial sequence compared to the short-short sequence. On the other hand, when the current foreperiod is long and follows a short foreperiod, predictions can be updated when the target does not appear after the short foreperiod. This way preparation can be optimal whatever the foreperiod of the preceding trial (Correa et al., 2006a; Karlin, 1959; Van der Lubbe et al., 2004). The fMTP (Los et al., 2017; Salet et al., 2022) proposes a slightly different explanation. According to the fMTP, sequential effects arise from the replay of the previous foreperiod. If the previous trial had a long foreperiod, an anticipatory response is prevented on the current trial by impeding a response during the short foreperiod. This also explains slower RT in long-short trial sequences compared to short-short sequences (Los, 2013; Los & Heslenfeld, 2005; Los & Van Den Heuvel, 2001).

The sequential effects are observed in simple and choice RT tasks, although Steinborn et al. (2008) suggested them to be stronger in simple RT procedures. Our tasks only require to react to the target signal without imposing a choice between different responses. This holds true even when the movement direction changes from trial-to-trial, as participants choose the direction for the next movement only after responding to the current target signal. Whatever the precise mechanisms of the sequential effects, the foreperiod of the previous trial can influence performance only if this foreperiod is expected, i.e. integrated in the preparation. Looking at sequential effects is thus a way to verify to which amount external time constraints are taken into account when planning an action. To that aim it is not enough to look at the response occurring after the stimulus, which might reflect the processing of the stimulus rather than the movement planning itself. We looked also at motor parameters preceding the processing of the signal, as well as at EEG signals known to be associated with the waiting period. Motor parameters prior to the target signal can be expected to be inherently associated with feed-forward motor planning, but not EEG

signals. Exploring these two types of parameters (motor and EEG) in parallel and at the same time period allows us to contrast parameters differentially related to motor planning. Among EEG signals, the contingent negative variation (CNV) is of special interest since it has been associated with temporal preparation processes. The CNV starts after the presentation of the first signal in a trial and persists until the onset of the target (Breska & Deouell, 2014; Correa et al., 2006a; Griffin & Nobre, 2003; Mento et al., 2013; Walter et al., 1964). The CNV is observed in many different tasks, like duration estimation (Kononowicz & Penney, 2016), sustained attention tasks (Kropp et al., 2001; Li et al., 2024), or in the stop signal procedure (Arjona et al., 2014). The CNV brain sources are multiple, as both the dorsolateral prefrontal cortex, the supplementary motor cortex, primary motor cortex, anterior cingulated cortex, basal ganglia, thalamus, orbitofrontal cortex, and even parietal areas and cerebellum are involved in the genesis of CNV (Basile et al., 2002; Fattapposta et al., 2024). Moreover, it has been shown that the CNV is influenced by various factors like the intensity of the warning signal (Loveless & Sanford, 1975), eye movements (Tecce, 1972; Weerts & Lang, 1973), expected rewards and motivation (Brunia et al., 2011; Frömer et al., 2021; McAdam et al., 1969), and attention (Arjona et al., 2014; Brunia, 1993; Mento, 2017). It is thus likely that the CNV reflects more than motor preparation. This is the case even in tasks that do not explicitly require attention, like in our motor task. In particular Mento et al. (2013) used a variable foreperiod task and dissociated the CNV from decisional processes and motor response. In their task, the foreperiod was constant in successive blocks, but no response was required. A CNV was observed during the foreperiod, and its amplitude became more negative as the task progressed, reflecting progressive learning of the temporal structure of the trials throughout the task. This implicit learning occurred even though the onset of the target was neither associated with a motor response nor with decision-making, suggesting the possibility of a motor-independent prediction. In parallel, sequential effects also influence the amplitude of the CNV in the variable foreperiod task: during the short foreperiod, the CNV amplitude is more negative if the previous foreperiod was also short rather than long (Capizzi et al., 2013; Los & Heslenfeld, 2005; Mento, 2013, 2017; Van der Lubbe et al., 2004). In all, the CNV is well suited to explore time expectation mechanisms beyond motor preparation.

Preliminary results had been obtained in a motor task in which participants had to change their movement from trial to trial. The results showed that sequential effects were absent

in kinematic parameters or behavioural responses when the movement changed from trial-to-trial. In contrast, sequential effects were observed on behavioural responses in the same participants with a simple RT task. Given these results and the fact that the movement was changed from trial to trial, it was possible that sequential effects disappeared because the program had to be reset. However, these results were obtained on a limited number of trials and required replication, especially given the supposed automaticity and replicability of the sequential effects. The unidirectional task was chosen to maximize our chance of observing sequential effects, while keeping the original multidirectional task unchanged. In the present study we contrast the CNV and the behavioural results in the tasks in which the movement does or does not change direction. Since the CNV reflects more than just motor preparation, sequential effects on CNV amplitude should be observed regardless of whether the motor program changes from trial-to-trial. Such results would show that the time characteristics of the previous trial have been retained. In contrast, the sequential effects at the behavioural level may be present or not, depending on the tasks. If preliminary results are replicated sequential effects disappear when the movement changes direction, it would replicate preliminary results and confirm that external time constraints do not necessarily influence the movement program. Moreover, sequential effects should be observed when the movement direction stays the same from trial-to-trial. Such a contrast between the two tasks would indicate that external time constraints can be integrated within the motor program (when the movement stays the same) but are not necessarily transferred to the next program (when the movement changes). To which amount this concerns the feed-forward inverse program or the adjustment of the action after the target signal is verified by looking at sequential effects on motor parameters preceding the target signal onset. If sequential effects are observed on parameters recorded before the stimulus onset, it would suggest that sequential effects affect the feed-forward inverse program, whereas if it affects only parameters recorded after the target signal it would mean that sequential effects are selectively used to adjust the reaction to the sensory information.

2. Materials and Methods

2.1. Participants

25 participants were recruited for this experiment, including 23 right-handed and 19 women. We calculated the sample size based on the sequential effects observed in a preliminary study using a simple RT task, with the formula: $N = 2*(phi*sd)^2/(m1-m2)^2$, where: phi = 3.242 (for a power of 90%), sd = 25.42 (the standard deviation of the RT difference between short foreperiods depending on the preceding trial), m1 and m2 = 315 ms and 347 ms, respectively (a 32 ms difference between RTs for short foreperiods preceded by either a short or long foreperiod). The calculation resulted in a minimum of 13 participants Given the use of a new task and EEG, the use of 16 participants in the manuscripts of Mento (2017), and the need to assert a lack of sequential effects in the multidirectional task, we multiplied the sample size by 2. This number corresponds to the one announced in the document written for the ethical committee. The average age (mean ± SD) was 22.72 ± 3.43 and years of education were 15.08 ± 1.58. Any neurological, psychiatric or addiction disorders was an exclusion criterion. None of the participants used cannabis in the last 2 months prior to the experiment, or any other psychotropic treatment. Participants with a history of head injury with a loss of consciousness lasting more than 15 minutes were not included.

All participants gave their informed written consent, and the study was conducted in accordance with the Declaration of Helsinki. The protocol received an agreement from the ethics committee of the University of Strasbourg (Unistra/CER/2019-24).

2.2. Equipment

Participants sat down in a dark and quiet room, in front of a box of 63 cm high, 60 cm wide and 47 cm deep. Before the beginning of the protocol, we showed the inside of the box to the participants so they could see that it was empty. Then, we instructed participants to put their dominant hand inside the box, fist closed, and index finger extended, so that they could start/stop linear movements inside the box. Precision Micro-Drives© vibro-tactile motors were attached to the forearm and wrist of the participants'

dominant arm. They were used to apply tactile stimuli to indicate when the movement should be started or stopped. The motors were connected to a Chronos E-Prime 3.0 stimulation box. The whole task was controlled by a Dell computer model OptiPle x9020 AIO and programmed on E-Prime 3.0. The intensity of the vibrations was set at 3.0 V, with a frequency of 230 Hz. Participants were provided with rubber earplugs to prevent them from hearing the vibrations. Before the beginning of the tasks, the box was covered with a thick black material so that participants could not see inside, and no light could come into the box. To record participants' index finger trajectories in the dark box, a red LED was attached to the participant's index fingernail, and the trajectory of the LED was recorded with a GoPro HERO7 black camera placed at a height of 63 cm. The video recording parameters were linear field of view, 120 Hz resolution, 16:9 full HD format.

2.3. Procedure

Our protocol consisted of three experimental tasks.

In the two motor experimental tasks of interest, participants were instructed to perform a movement in a straight line following a tactile vibration of 100 ms applied to the forearm (start signal) and to stop it as fast as possible following a tactile vibration of 100 ms applied to the wrist (target signal). The different locations of the vibrations (forearm and wrist) made it easy for the participants to distinguish the start and target signals. The target signal occurred at variable foreperiods after the start signal, either 1000 ms (short foreperiod) or 1700 ms (long foreperiod). The foreperiods were set to ensure that the shortest one (1000 ms) allows participants to perform a long enough action. The long foreperiod (1700 ms) was selected to be distinct from the short one while remaining short enough to keep participants from reaching the edge of the box.

The two experimental tasks differed mainly in the type of performed movement. In the multidirectional task, participants had to change the direction of their movement from one trial to another, as they might have done if they were exploring a maze. As in a maze, movements were restricted to the X and Y axes (horizontal and vertical directions). In the unidirectional task, participants began each trial from the same position, ensuring that they always moved in the same direction. To make the beginning of the next trial unpredictable, we used a variable inter-trial interval (ITI) ranging from 2000 to 2300 ms.

In each experimental task there were 240 trials, 120 with a short and 120 with a long foreperiod, randomly distributed.

Before starting each task, a training phase of 10 trials was conducted to familiarize participants with the tasks. During this phase, the experimenter visually ensured that participants initiated their movement with the start signal and stopped with the target signal. The speed of their movements was also visually monitored during this training phase to prevent them from going too fast and reaching the box edge, or too slow and showing a jerky trajectory. The experimenter thus ensured that all participants made movements with similar speeds, even if those were not strictly identical. On occasion, some participants did collide with a box side. In such cases, the instruction was to completely stop the movement and remain still until the next trial. This instruction allowed us to identify these trials as anticipations, enabling us to exclude them from further analysis.

In the third control task, participants had to press a button as fast as possible in response to a target. This task allowed us to verify that our sample showed the temporal prediction indicators (variable foreperiod and sequential effects) commonly observed on RTs in a typical variable foreperiod protocol. As this control task was not relevant to our main question, this task's methodology and results can be found in the Supplementary Material - Section 1.

2.4. Electroencephalography

During the tasks, EEG activity was recorded using the ActiveTwo Biosemi system (Amsterdam, Netherlands) with 64 actives Ag/AgCl electrodes mounted according to the 10-20 international system. Electrodes were distributed over the scalp according to the international 10-20 system. The ground electrode was composed of the Common Mode Sense (CMS) and the Driven Right Leg (DRL) electrodes. Acquisition quality was ensured by keeping the electrode offset (average voltage relative to the CMS) below 50 mV. Flat-type electrodes were placed on the left and right earlobes for future referencing. No online filter was applied, and the signal was sampled at 2048 Hz.

This EEG system is based on active electrodes, which transform impedance as follows: the input impedance is very high (300 Mohm), while the output impedance is very low (< 1 Ohm). This way, the interference currents flow via very low impedances (the output of the active electrode) and cannot generate significant interference voltages. In addition, the electrode impedance does not affect the level of interference.

2.5. Data analyses

2.5.1. Behavioural data

We recorded participants' motor trajectories and analysed behavioural indicators from the collected video images on MATLAB 2021b.

We segmented our videos into 240 trials of 3000 ms. The beginning of each trial was defined by the onset of the start signal (i.e. the first tactile vibration on the forearm). It was recorded by the camera thanks to a blue LED inside the box that lit up at the onset of the forearm vibration and lasted for 100 ms, i.e. until the offset of the vibration. Similarly, when the target signal occurred (i.e. the second tactile vibration on the wrist), a green LED inside the box lit up during the entire wrist vibration.

We analysed the trajectory of the finger (i.e. of the led) with MATLAB. We established several criteria to enable the script to identify the indicators defined in the following. The criteria are described below.

2.5.1.1. Stopping latency or RT

We collected participants' stopping latencies i.e. the delay they needed to stop their movement after the target signal. The stopping latency was used as a RT in our protocol. RT is the indicator commonly used to assess participants' performance in variable foreperiod paradigms (see our control task in Supplementary Material – Section 1) and allowed us to extrapolate typical behavioural indicators of temporal prediction abilities in our two motor tasks. In both experimental tasks, the stopping point was defined as the first point where all our criteria (see below) were met. If no point satisfied the stopping criteria, the trial was excluded from further analyses. If the movement had been stopped

before 150 ms after the target signal, this stop was considered as anticipated, and the trial was excluded from further analyses. As a matter of fact, the time it takes to process the target, to make a decision and to send a motor command back means that the reaction is necessarily delayed relative to the target stimulus (Jana et al., 2020). Trials that were 'anticipated' and subsequently excluded include true anticipations as well as instances where participants reached the limits of the box. When they hit the box limits before the end of the trial, they were instructed to halt their movement before the target signal occurred, and the action was thus considered an anticipated stop.

RT was defined as the time difference between the onset of the target signal and the moment participants stopped their movement. At the stopping point, the participants' speed was never exactly zero. If their index finger was shaking a little, a movement was detected and the speed, though small, was not equal to zero (see Figure 1). Therefore, we had to define criteria allowing us to consider the movement to be stopped. A second difficulty was that not all participants were moving at exactly the same speed, and we could not define a unique speed threshold below which the movement would be considered as being stopped. Therefore, we used slowdown percentages rather than exact speed values. To ensure that the criteria allowed us to detect the stopping point correctly, each trial in each participant was visually inspected using a graphical representation of the speed over time. We verified whether the stopping point placed by our script was where common sense would have placed it.

For the multidirectional task, an average of 2 trials out of 120 trials per participant were excluded in case of a short and long foreperiod respectively. A total of 90 and 89 trials per participant were included for the short and long foreperiod respectively.

For the unidirectional task, an average of 6 and 9 trials out of 120 trials per participant were excluded in the short and long foreperiod respectively. A total of 87 and 82 trials per participant were included for the short and long foreperiod respectively.

2.5.1.1.1. Stopping point criteria in the multidirectional task

An example of how speed varies during the trajectory in a trial is depicted in Figure 1. We refer to each maximum and minimum speed as a 'speed peak' (see Figure 1). In the

remainder of the text, when criteria refer to both minimum and maximum speed, the generic term ‘peak’ will be used. Otherwise, we will specify whether the criterion concerns a maximum or a minimum speed.

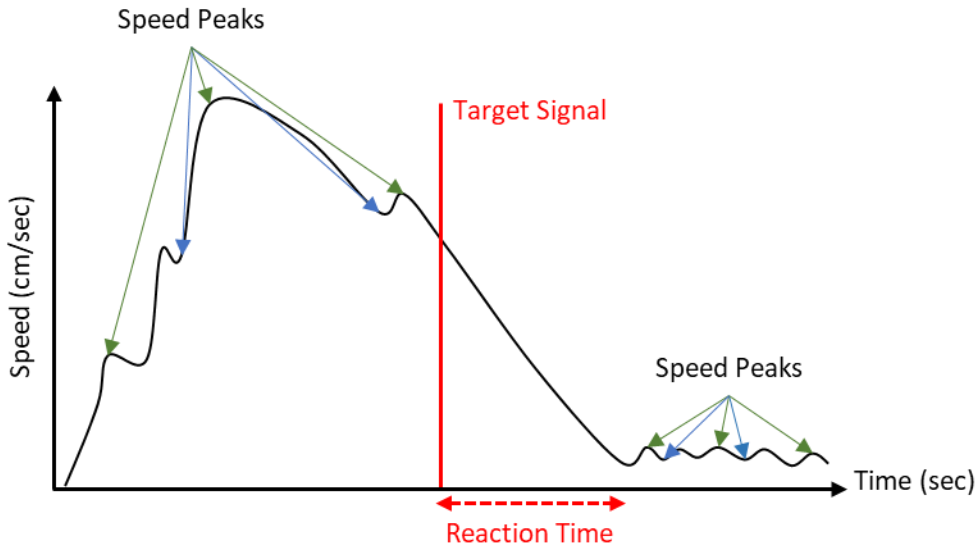

Figure 1. There is an initial acceleration due to the start signal. During this acceleration, speed can vary, leading to speed peaks. Green arrows indicate maxima, while blue arrows indicate minima. After 1 second, the target signal occurs (red line on the graph), and the delay needed to stop the action represents the stopping latency (i.e. RT). Even though participants no longer continue their movement, small speed peaks, due to tremors, are still detected.

A first criterion for the stopping point was that speed had to be slowed down by at least 40% compared to the previous maximum speed. For example, if the previous maximum speed was 10 cm/sec, the speed at the stopping point had to be lower or equal to 6 cm/sec. This criterion allowed us to detect a significant slowdown, but was not enough to determine a stopping point, as it may happen that a participant's speed decreases, without necessarily stopping. We added a second criterion to ensure that the participant was not re-accelerating. A stopping point was identified as such only if the next two speed peaks were less than twice the speed at the stopping point. According to the previous example, if the speed at the stopping point was 6 cm/sec, then the speed at the two next speed peaks had to be strictly lower than 12 cm/sec. These two criteria still did not guarantee that the movement was truly stopped. We needed to establish a speed threshold below which we could consider the participants’ index finger was no longer moving. As emphasized, due

to tremors, the speed was never equal to zero. Instead of using zero speed, we decided to use the tremors-related speed as a threshold at the stopping point. To determine the tremor-related speed, we used the median speed peak of each trial (between 0 and 3 seconds). The median speed peak was reliable because trajectory-related speed changes exhibited a linear variation with few peaks, whereas tremors-related peaks displayed irregular patterns with multiple small peaks (see Figure 1). Due to the high number of peaks during tremor, the median speed peak was always tremors-related. The third criterion was that the speed at the stopping point had to be less than or equal to 1.5 times the median speed peak of this trial. If we take the previous example, with a speed of 6 cm/sec at the stopping point, the median speed peak of the trial had to be equal or lower than 9 cm/sec. The combination of these three criteria allowed our program to detect stopping points in an objective and accurate way, as verified with visual inspection.

2.5.1.1.2. Stopping point criteria in the unidirectional task

The criteria for the stopping point had to be adapted for the unidirectional task. In this task, after having stopped their movement, participants returned to the starting position before the onset of the next trial. The stop was therefore not as clear and the standstill period not as long as in the multidirectional task. Hence, we adapted the stopping criteria as follows: at the stopping point, the speed of the movement had to be slowed down by at least 30% compared to the previous maximum speed (instead of 40% in the multidirectional task). The second criterion was the same as in the multidirectional task: a stopping point was identified as such only if the next two speed peaks were less than twice the speed at the stopping point. When the standstill period was not long enough, the two next speed peaks after the stop could not be less than twice the speed at the stopping point. As a matter of fact, when participants went back to their starting position after stopping their movement, they usually did it so quickly that the following speed peak was the highest speed peak of the trial. If a short standstill period was detected, then a stopping point was identified as such only if the speed at the next maximum was at least 50% of the maximum speed of this trial. Finally, to ensure that the movement had truly stopped, we added a last criterion based on the speed itself at the stopping point, which had to be lower or equal to 35% of the maximum speed associated with returning to the starting position. The value of 35% was verified by visual inspection: stopping points would have been missed with a lower percentage.

2.5.1.2. Deceleration points

Participants slow down their movement in anticipation of the movement end. Such slowing down is characteristic of the movement kinematics and indicates how and when the movement end is prepared for in the motor program (Duque et al., 2017; Woodworth, 1899). The start of this slowing down was taken as a proxy for the moment when preparation to stop the movement started. In the following, we will refer to this slowing down as the 'deceleration point' for the sake of simplicity. Since we have two foreperiods in each task, we were interested in the deceleration point before the onset of the target signal at 1000 ms (short foreperiod) which we will call the 'first deceleration point'. The second deceleration point between 1000 ms and 1700 ms (long foreperiod) did not bring much more to the results, and we focus on the first deceleration point for the sake of simplicity. Results related to the second deceleration point can be found in the Supplementary Material – Section 2. Before 1000 ms, participants could not know when the target signal would occur, and for this reason a first deceleration point was expected in all trials (short and long foreperiods). The criteria used to identify the first deceleration point were identical between the tasks. First deceleration points were defined as the first slowing down where all our criteria were met.

2.5.1.2.1. First deceleration point (150 – 1000 ms) criteria

For the first deceleration point, we defined a temporal period from 150 until 1000 ms. At least 150 ms are needed for the start signal to be processed and a motor command to be sent back (Jana et al., 2020). Hence deceleration point below 150 ms was considered as an anticipation. If the target signal was expected at 1000 ms, slowing down should start before 1000 ms. As for the stopping point criteria, we verified the consistency of our criteria, described hereafter, by visual inspection, for each trial in each participant.

A first criterion was that the speed at the first deceleration point had to be at least equal to 30% of the maximal speed in the time window of interest. Visual inspection suggested the criterion of 30% of the maximum speed was a good compromise between the risk of omission and false alarms. The two additional criteria ensured that participants were decelerating their movement and not preparing to accelerate further. The speed at the next speed peak had to be at least 10% slower than the speed at the first deceleration point,

and/or the acceleration at the next speed peak had to be at least 30% lower than the acceleration at the first deceleration point.

Several additional indicators were derived from the deceleration point. In order to describe the data, we measured the speed at this point and the latency, i.e. the delay between the start of the trial and the first deceleration point (results regarding the latency can be found in the Supplementary Material – Section 2). However, the main parameter was the deceleration slope in between the first deceleration point and the target signal (in case of a short foreperiod), which evaluates the efficiency of the slowing down in anticipation of the target signal. We calculated the relative deceleration slope according to this formula: [(speed at the first deceleration point – speed at 950 ms) / speed at the first deceleration point] in all trials. We used the speed at 950 ms instead of the speed at 1000 ms to avoid a potential effect of the onset of the target signal in trials with a short foreperiod.

2.5.2. Electrophysiological data

The EEG analysis was performed on MATLAB R2021b with the EEGlab toolbox (Delorme & Makeig, 2004).

The pre-processing steps were applied to each participant and for each task separately. First, we referenced our signal with our bipolar electrodes attached to the right and left ears. Then we reduced the sampling rate from 2048 to 512 Hz to keep a good temporal resolution while reducing the analyses time. The data was band-pass filtered between 0.01 and 30 Hz (Mento, 2017). We then applied additional cleaning and filtering steps to create an optimal dataset for the application of the ICA 'runica' algorithm proposed by EEGlab (Luck, 2022). An average of 3 ± 3 electrodes per participant were interpolated (a maximum of 12 electrodes interpolated in two participants whose EEG signal was particularly noisy; none concerned our electrodes of interest).

We segmented our trials 200 ms before the onset of the start signal and up to 2000 ms after. The baseline was defined as the average EEG signal from 200 ms before to the onset of the start signal i.e. [-200 0] ms. Subsequently, we rejected artefacts appearing 200 ms before the onset of the start signal and until the target signal in the long foreperiod i.e. [-

200 1700 ms] using a single voltage threshold ± 150 µV. An average of 110 out of 120 trials were included for both the short and long foreperiods in the multidirectional task, vs. 113/120 and 112/120 trials in the unidirectional task, for the short and long foreperiods respectively. For three participants, the data was too noisy due to sweating artefacts, and was excluded from the analyses, bringing our group to 22 participants for our EEG data.

2.5.3. Statistical analyses

Statistical analyses were carried out in R (RStudio Team, 2016). For all the indicators, we worked with the median values of each participant (to avoid difficult decisions about outliers cutoff values). The graphs display the data averaged across participants. Error bars represent the standard error of the mean (SEM).

For our statistical comparisons we performed repeated measures ANOVAs to examine interaction effects that are well-established in the literature (Correa et al., 2006a; Martin et al., 2017; Mento, 2017). When the assumption of normal distribution was not met in our datasets, we normalized them before conducting the ANOVA. To do so, we used the 'boxcox' function from the 'bestnormalize' R package, which enabled our datasets to conform to a normal distribution (Box & Cox, 1964). This approach was predetermined in the ethical document. To keep a normal distribution while preserving a mean and a standard deviation different from 0 and 1 respectively, we applied inverse z-scores to our datasets before conducting the statistical analysis. Overall, the level of significance was set to $\alpha = 0.05$. The partial eta-squared (η^2_p) values are added as a measure of effect size.

3. Results

3.1. Reaction times

We verified whether the previous and current foreperiods had an influence on RTs on the current trial. The purpose of this analysis is to ensure the presence of the typical indicators of temporal prediction abilities on RTs: as a reminder the decrease of RTs with increasing foreperiods reflects the variable forepriod effect, whereas the increase of RTs when the previous and current foreperiods are respectively long and short (vs. short on both trials)

reflects sequential effects. As already emphasized in the methods section (2.3. Procedure) sequential effects are not expected at long foreperiods. We focus on the typical effects, but full statistical analyses can be found in Supplementary Material – Section 2. We performed a three-factor repeated measures ANOVA on participants' RTs with the within-group factors 'task' (unidirectional vs. multidirectional), 'previous foreperiod' (short vs. long) and 'current foreperiod' (short vs. long) (Figure 2).

The three-factor ANOVA on RTs revealed a main effect of 'task' [$F(1,24) = 19.19$, $p = 0.0002$, $\eta^2_p = 0.44$], with faster RTs in the unidirectional (351 ms ± 87.1) than in the multidirectional task (432 ms ± 82.0). There was also a main effect of 'current foreperiod' [$F(1,24) = 161.41$, $p = 0.000000000004$, $\eta^2_p = 0.87$]. This effect reflects a typical variable foreperiod effect, with RTs being faster when the current foreperiod was long (344 ms ± 65.9) rather than short (438 ms ± 93.7). There was finally a main effect of 'previous foreperiod' [$F(1,24) = 45.21$, $p = 0.0000006$, $\eta^2_p = 0.65$], with longer RTs when it was preceded by a trial with a long (401 ms ± 93.6) rather than short (382 ms ± 93.2) foreperiod.

The factor 'previous foreperiod' interacted significantly with the factor 'current foreperiod' [$F(1,24) = 22.04$, $p = 0.00009$, $\eta^2_p = 0.48$]. A paired t-test confirmed the typical asymmetric sequential effects since RTs increased only when the foreperiod of the current trial was short and the previous foreperiod was long (456 ms ± 84.5) rather than short (421 ms ± 99.7), $t(49) = -6.08$, $p = 0.0000002$.

There was a significant interaction between the three factors 'current foreperiod', 'previous foreperiod' and 'task' (unidirectional vs. multidirectional) [$F(1,24) = 16.08$, $p = 0.0005$, $\eta^2_p = 0.40$]. In the unidirectional task, we observed a significant interaction between the factors 'previous foreperiod' and 'current foreperiod' [$F(1,24) = 55.38$, $p = 0.0000001$, $\eta^2_p = 0.70$], but not in the multidirectional task [$F(1,24) = 0.70$, $p = 0.4$, $\eta^2_p = 0.03$]. In the unidirectional task, we found the typical sequential effects: there was a main effect of 'previous foreperiod' only when the current foreperiod was short [$F(1,24) = 73.80$, $p = 0.000000009$, $\eta^2_p = 0.76$]. RTs on the current trial with a short foreperiod were longer when the previous foreperiod was long (415 ms ± 82.6) rather than long (358 ms ± 80.4).

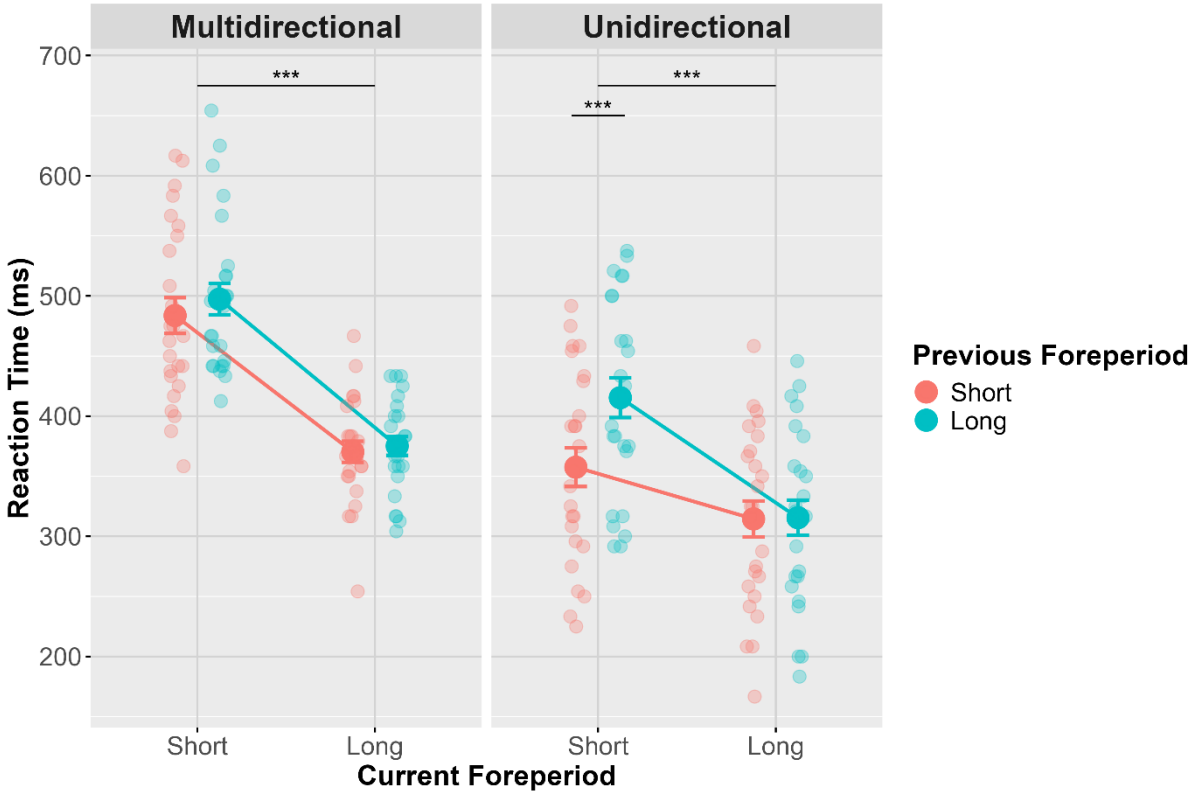

Figure 2. RTs in ms on the current trial in both motor tasks, depending on the previous foreperiod. Opaque shapes with error bars show the mean RTs ± SEM, while transparent shapes reflect individual participants' data points in each condition. Statistical significance is denoted by *** for p-values < .001. The asterisks between the current short and long foreperiods indicate the main effect of the 'current foreperiod' factor. The asterisks above the two leftmost points on the right panel (approximately 350 ms and 410 ms), signal an effect of the 'previous foreperiod' factor at the current short foreperiod in the unidirectional task.

3.2. Relative deceleration slope before 1000 ms

The trajectory reveals how the stop is anticipated. Such markers are not comparable across short and long intervals, and here we focus on sequential effects rather than on the variable foreperiod effect, and we consider only the deceleration before 1000 ms, i.e. within the short foreperiod interval (see paragraph 2.5.1.2). This means that the factor 'variable foreperiod' was not taken into account. As a reminder the deceleration occurs before the target, and all trials were taken into consideration (with a short or a long foreperiod). If the motor prediction is influenced by preceding trials, it leads to sequential effects. In this section, we explored the effect of the previous foreperiod on the relative

deceleration slope of the current trial. We first report a one-factor ANOVA in each experimental motor task separately, as those tasks are new, and as the two tasks were conducted separately, in distinct blocks. Since the previous foreperiod influenced the relative deceleration slope differently in our two experimental tasks, we conducted an additional analysis, with the within factor 'task' (unidirectional vs. multidirectional) to verify whether results in the two tasks significantly differed (Figure 3).

In the unidirectional task, the one-factor ANOVA on relative deceleration slope showed a main effect of 'previous foreperiod' [$F(1,24) = 10.70$, $p = 0.003$, $\eta^2_p = 0.31$]. Participants showed a shallower relative deceleration slope when the previous foreperiod was long (0.153 ± 0.1) rather than short (0.194 ± 0.1).

In the multidirectional task, the one-factor ANOVA showed no main effect of 'previous foreperiod' on the relative deceleration slope [$F(1,24) = 0.84$, $p = 0.4$, $\eta^2_p = 0.03$].

To compare the two experimental tasks (Figure 3), we performed a two-factor ANOVA on the relative deceleration slope of the current trial. A significant interaction between the factors was found [$F(1,24) = 4.67$, $p = 0.04$, $\eta^2_p = 0.19$], confirming the difference between the two tasks.

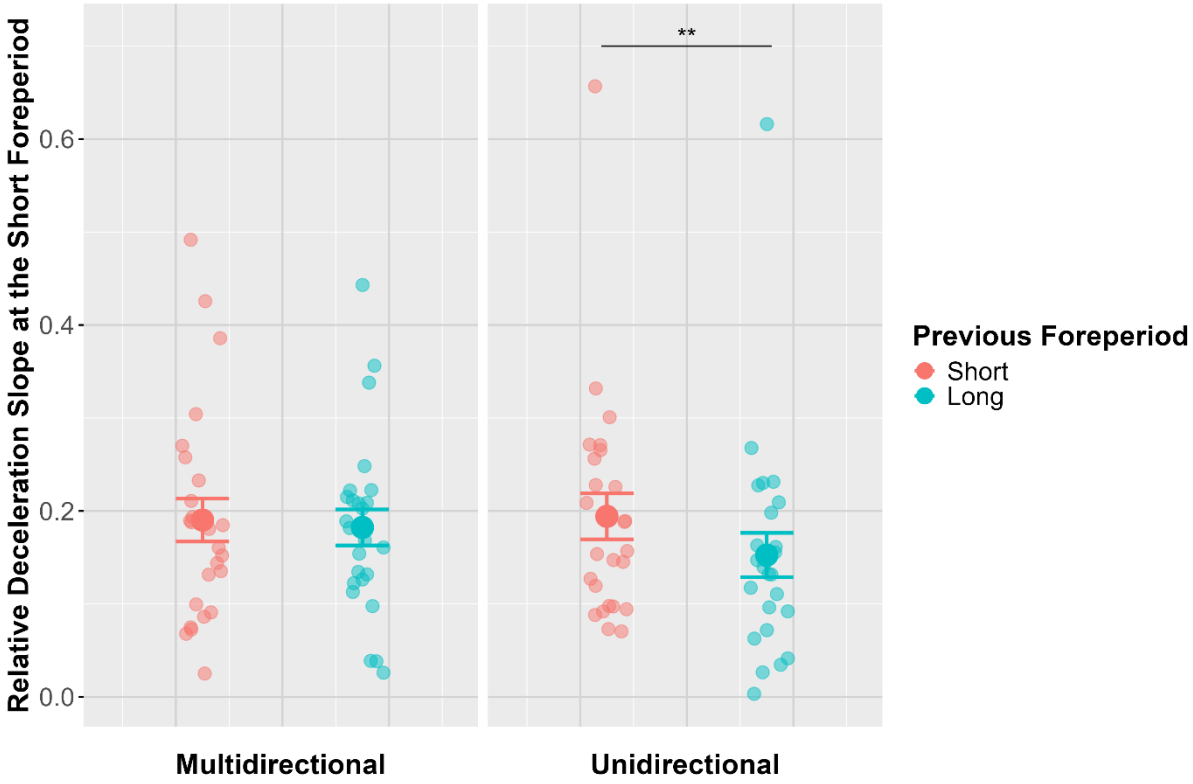

Figure 3. Relative deceleration slopes in all current trials (i.e. regardless of their foreperiod) in both motor tasks, depending on the previous foreperiod. This indicator shows how participants decelerate from the first deceleration point to the onset of the target signal at short foreperiod (we take into account the moment just preceding the onset, in order to avoid vibration-related artefacts). Opaque shapes with error bars show the mean relative deceleration slope ± SEM, while transparent shapes reflect individual participants' data points in each condition. Statistical significance is denoted by ** for p-value < .01.

3.3. CNV

We verified whether sequential effects were observed on the CNV amplitude in both tasks, despite the absence of sequential effect on the behavioural indicators in the multidirectional task. To do so, we performed a two-factor ANOVA with the within-group factors 'task' (unidirectional vs. multidirectional) and ‘previous foreperiod’ (short vs. long) on the mean amplitude of the CNV on the current trial (measured between 800 and 1000 ms) (Figure 4). In this time window we are right before the onset of the target signal in case of a short foreperiod. Since participants do not know whether the foreperiod will be short or long we averaged data over both foreperiods. We focused our analysis on FCz,

Cz and C1 electrodes which are traditionally used to observe the CNV (Capizzi et al., 2013; Foerster et al., 2022; Kononowicz & Penney, 2016; Kononowicz & Van Rijn, 2011; Macar et al., 1999).

The two-factor ANOVA on CNV amplitude revealed a main effect of 'previous foreperiod' [$F(1,21) = 9.63$, $p = 0.005$, $\eta^2_p = 0.31$], with a less negative CNV amplitude when the previous foreperiod was long (-1 u.a ± 3.2) rather than short (-2.4 u.a ± 4). We found no main effect of 'task': [$F(1,21) = 0.71$, $p = 0.4$, $\eta^2_p = 0.03$] nor any interaction between the factors [$F(1,21) = 0.22$, $p = 0.6$, $\eta^2_p = 0.01$]. This was expected, since we had anticipated sequential effects on the CNV in both tasks. Nonetheless, to make sure that a sequential effect can indeed be found in both tasks, we performed one-factor ANOVAs in each task, which are available in Supplementary Material – Section 2.

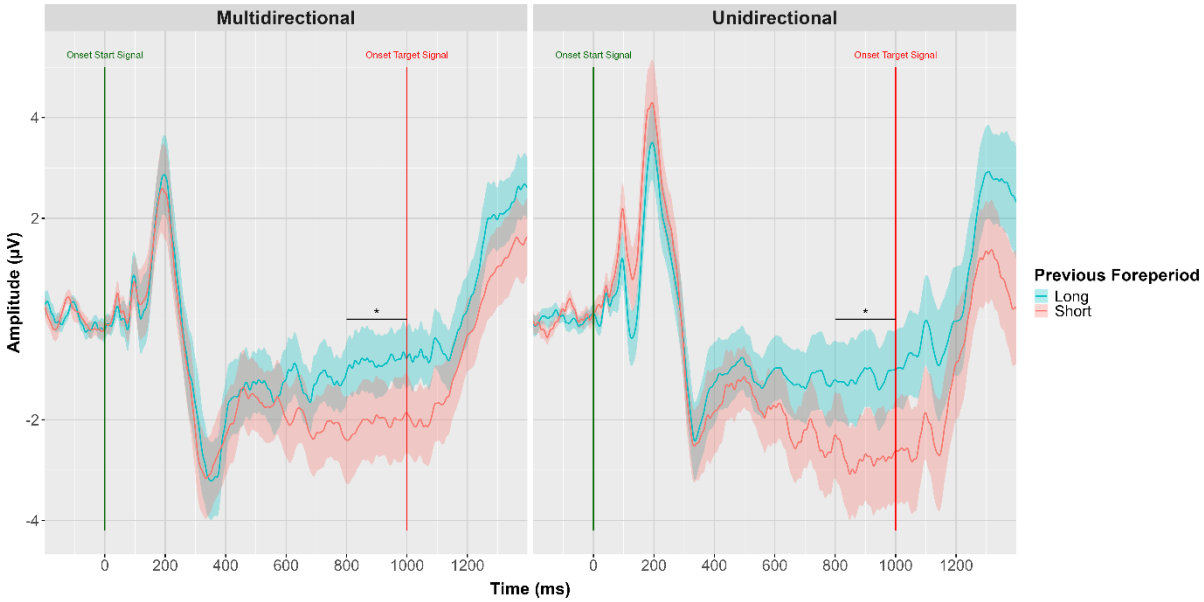

Figure 4. CNV amplitudes in µV in multi- and unidirectional tasks (panel A and B respectively), averaged across three electrodes (FCz, Cz, and C1) in all current trials (i.e. regardless of their foreperiod). The shaded area around the lines corresponds to the SEM. 0 ms on the abscissa marks the onset of the start signal (green line), while 1000 ms marks the onset of the target signal at the short foreperiod (red line). Statistical analyses were conducted on the average CNV amplitude in the 800-1000 ms window. Statistical significance is indicated by * for p-values < .05.

As a reminder, no sequential effect is expected at the long foreperiod. The CNV are nonetheless illustrated in Supplementary Material – Section 2. The analysis shows that there is no difference in the CNV amplitude at the long foreperiod between the two tasks, and only a trend in the decrease of the CNV amplitude at long relative to short foreperiod.

4. Discussion

The aim of this study was to understand whether a temporal prediction is specifically attached to the motor action. We combined two motor tasks with the variable foreperiod paradigm. In the unidirectional task, participants repeated the same movement direction from trial-to-trial, while in the multidirectional task, they were asked to change direction from trial-to-trial. We replicated the usual variable foreperiod effect in both motor tasks (see Supplementary Material – Section 1 for the control task), despite our change of protocol. Moreover, we collected kinematic parameters during the foreperiod, in addition to typical indicators of temporal prediction abilities (RT and CNV) and assessed sequential effects. The latter are thought to be robust markers of automatic temporal prediction abilities (Kong et al., 2015; Vallesi et al., 2014). Parameters similarly influenced by sequential effects in both tasks indicate a temporal prediction independent from the specific motor program, while those observed only in the unidirectional task may reflect a motor-related temporal prediction.

Regarding the EEG results, sequential effects were observed on the CNV amplitude in our control task (see Supplementary Material – Section 1) and in both motor tasks. Regardless of the motor direction taken by participants from trial-to-trial, we observed an impact of the previous foreperiod on participants' EEG-related preparation on the current trial. The presence of sequential effects on the CNV amplitude in a variable foreperiod task has been extensively described in the literature, contributing to establishing CNV as an EEG indicator of temporal prediction abilities (Breska & Deouell, 2014; Mento, 2017; Van der Lubbe et al., 2004; Walter et al., 1964). Our results are consistent with those previous findings.

Sequential effects were not expected when the current foreperiod was long. For both the hazard-based theory and for the fMTP there is no influence from the preceding

foreperiods at long foreperiods (see Supplementary Material – Section 2), and this is also what is usually seen in the literature (Correa et al., 2006b; Los et al., 2017; Niemi & Näätänen, 1981; Vallesi et al., 2007; Zahn et al., 1963). This might be seen as in contradiction with the study of McAdam et al. (1969). However, in this study participants were required to emit an explicit prediction regarding the next foreperiod on each trial. The authors measured the impact of this prediction rather than the implicit impact of the recent foreperiod, which probably explains the discrepancy with our results and the literature.

Regarding the behavioural results, we observed sequential effects on RT in the control task (see Supplementary Material – Section 1) and in the unidirectional task only. In addition, in the unidirectional task, we observed sequential effects on the anticipatory deceleration of the movement. In the multidirectional task, these sequential effects were not present. In other words, sequential effects are observed when the same movement is repeated from trial-to-trial but disappear when the movement direction changes. This suggests that sequential effects on behavioural indicators reflect the existence of a motor-related temporal prediction. We first detail behavioural results before discussing why we observe a difference in sequential effects between behavioural and EEG responses.

Slowing down (decelerating) before the end of a movement has long been described (Woodworth, 1899). It is intrinsic to the motor program itself as it helps to avoid any unwanted collision, e.g. before reaching an obstacle. The timing and the way this slowdown occurs indicate how the end of the movement is prepared for and provide important insights into the motor preparation occurring before the target signal. The characteristics of the deceleration allow us to assess sequential effects, which demonstrate how motor-related predictions are adjusted based on recent experiences, whether the movement direction changes (multidirectional task) or remains the same (unidirectional task).

In the unidirectional task, with short foreperiods, we observed sequential effects on the relative deceleration slope, likely reflecting a temporal prediction. As a reminder, the relative deceleration slope was calculated as (speed at the first deceleration point – speed before target signal at short foreperiod) / speed at the first deceleration point. If the previous foreperiod had been short, the relative deceleration slope was steeper than if the

previous foreperiod had been long. A steeper slope indicates increased deceleration without requiring additional time. The slope is steeper because it starts from a higher speed (at the deceleration point). This result may seem counterintuitive. After a short foreperiod, the next foreperiod is predicted to be short, due to sequential effects. A shorter foreperiod would be expected to lead to earlier deceleration (see Supplementary Material – Section 2), and slower speed. This was not observed. What is observed in the unidirectional task is increased deceleration when the previous foreperiod was short as compared to long. It is as if the repetition of the movement from trial-to-trial helps to optimize the deceleration phase. In contrast, when participants change direction from one trial to the next (multidirectional task), no sequential effects were observed on behaviour. The change in movement appears to preclude an optimization of the deceleration phase.

Behavioural parameters do not seem to be sensitive to the prediction of the onset of the target signal, i.e. the sensory signal, which was identical in the uni- and multidirectional tasks. If they were, we would have observed sequential effects in both tasks. One might assume that since deceleration occurs during the trajectory itself, it is not surprising that the sequential effects on this indicator reflect a motor-related temporal prediction. Yet the detrimental impact of the direction changes on sequential effects persists on RT. RT is closer to the typical measure in variable foreperiod tasks. It is a compound measure since it stems from a motor response to a sensory stimulus (Faugeras & Naccache, 2016; Niu et al., 2018). As such, it should be sensitive to both the prediction of the onset of the sensory signal and motor preparation. Especially the moment at which the target signal occurred on the previous trial might have been expected to be considered in the current trial. This is not the case, suggesting that motor prediction needs to be renewed when the movement changes. This need may explain why movement and RT are slower in the multidirectional task than in the unidirectional task. It might have been argued that the lack of sequential effect in the multidirectional task relates to the fact that responses in our protocol require motor inhibition (stopping the movement) rather than motor activation (pressing a button). However sequential effects have been widely documented across various task types (Brulé et al., 2021; Los, 2010; Marques-Carneiro et al., 2020; Wehrman et al., 2018). Importantly they are replicated in the unidirectional task, consistent with the literature emphasizing the importance of motor optimization in the sequential effects (Correa et al., 2006b; Los et al., 2017; Niemi & Näätänen, 1981; Salet

et al., 2022; Vallesi et al., 2007; Zahn et al., 1963). It is thus unlikely that the need to stop the movement explains the lack of sensitivity to the prediction of the target signal onset.

Our behavioural results seem especially sensitive to the motor anticipation. The fact that in the unidirectional task, we found sequential effects on the relative deceleration slope and not on its onset (latency) suggests that temporal prediction abilities play a role on how the movement is executed and not on its initiation. How this fits with explorations regarding the Smith predictor remain to be determined, given the difference in the tasks across protocols (Miall & Jackson, 2006). However, our results clearly suggest the existence of a specific motor-related temporal prediction. Inasmuch as this effect precedes the target signal, it suggests an effect on the inverse 'feed-forward program' rather than on the forward model that adjusts the movement to sensory feedbacks.

It could be argued that, for some reason, time expectations for long foreperiods differ between the uni- and multidirectional tasks, thus explaining the lack of sequential effects in the multidirectional task. If the long foreperiod is not expected as efficiently in the multidirectional task as in the unidirectional task, its influence in the subsequent trial might decrease. As a matter of fact, some older studies using foreperiods longer than 2 seconds have shown decreases in the CNV amplitudes for the longest foreperiods (Loveless & Sanford, 1975; McAdam et al., 1969). However, such long foreperiods can be expected to require executive functions to maintain expectation (Zélanti & Droit-Volet, 2011), and are clearly longer than the longest foreperiod used in our study (1700 ms). Our results do not show a decrease in expectation with time, albeit there is a tendency. Most importantly there was no difference between tasks for long foreperiods. The foreperiod effects show consistent time expectations in both tasks, as shown by the decreases in RT with increasing foreperiods, and the similar CNV amplitude between tasks at long foreperiods (see Supplementary Material – Section 2).

Our task being novel, we might discuss its sensitivity. For example, one might assume that our parameters are not sufficiently sensitive to small-amplitude sequential effects in the multidirectional task due to variability in the movement. It is important to emphasize that deceleration points were detected as easily in both tasks: on average, velocity peaks were found in 95% of trials for each participant in the multidirectional task and in 94% of trials for each participant in the unidirectional task. Also, the main effect of variable

foreperiod was found to be significant in both tasks (see the results and the Supplementary Material – Section 2), suggesting that the parameters were sensitive enough in both the uni- and multidirectional tasks.

Nevertheless, temporal prediction is still implemented in the multidirectional task, as evidenced by the results related to the amplitude of the CNV. The amplitude of the CNV was less negative when the previous foreperiod was long rather than short. This observation holds true in both of our motor tasks. While the CNV could reflect motor preparation (Macar & Besson, 1985; Walter et al., 1964), it might offer insights into a more general preparation, irrespective of the specific movement, due to the need to prepare in time for the target signal. Many studies have suggested a distinction between early and late CNV components, the former being related to attention orientation after the first stimulus (Weerts & Lang, 1973), and the later to motor preparation (Loveless & Sanford, 1975). It has been made clear that the late CNV differs from the lateralized preparation potential (LRP) (Ulrich et al., 1998) though. Ulrich et al. (1998) cued the movement to be executed with information on hand, direction, and force of the movement. They showed that, in contrast with LRP, the late CNV increased with the amount of prior information. They proposed that the CNV represents the assembling of the motor program, including any external influence helping to build the program. Gomez et al., (2003) used source localization and suggested that the late CNV is involved also in perceptual preparation, with a perceptual and motor coordination mediated by the frontal cortex. It is beyond the goal of the present study to discuss the exact functions reflected by the CNV. However, we can note that the slope of deceleration is a purely motor-related signal preceding the target signal. This motor parameter is modulated by sequential effects in the unidirectional task, but not in the multidirectional task, whereas the CNV amplitude is modulated by sequential effects in both tasks. Our results suggest that the CNV is unlikely reflecting a pure motor measure, and those results are in accordance with the literature. The CNV amplitude could reflect proactive anticipation of the target's onset, preparing for the detection, decision and response that need to be made as soon as the target appears (Correa et al., 2005; Correa et al., 2006c; Vangkilde et al., 2012). Future studies may benefit from the present procedure to distinguish between perceptual and motor functions. Such future studies may also address a limitation of our approach, which is the fact that the uni- and multidirectional tasks differ not only by the direction change between trial, but also by the need to decide the direction in the multidirectional task.

Devising intermediate experimental steps (e.g. with no choice but still a change in direction) may help to explore further the question of the distinction between the perceptual and motor components of time prediction and understanding at which point sensory and motor time prediction become disconnected, like they are in the multidirectional task.

5. Conclusion

Our results suggest that CNV amplitude is influenced by additional mechanisms not reflected in our behavioural indicators. In this sense, they confirm the existence of different mechanisms of temporal prediction abilities, as behavioural performance is affected by experimental manipulations, whereas EEG is not. In all, our results suggest two types of temporal prediction at the same temporal scale: one is motor-related, linked to the movement itself and visible on behavioural indicators (in the unidirectional task and before the target onset), while the other involves mechanisms that are independent from the movement and visible on the EEG indicator. These results raise questions regarding how the different mechanisms of the prediction interact, and whether motor prediction is embedded in a more general one. Similarly, given the neurodevelopmental component of temporal prediction abilities (Bender et al., 2005; Johnson et al., 2015; Mento & Valenza, 2016), it will be interesting to investigate whether these mechanisms of the prediction are established simultaneously during development or if one precedes the other. Most importantly, our task provides a useful tool to distinguish different types of temporal prediction impairments in pathological conditions.

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Author Contribution

Alana Arrouet: Methodology, Software, Validation, Formal analysis, Investigation, Data Curation, Writing - Original Draft, Visualization. José Eduardo Marques-Carneiro:

Methodology, Software. Pierre Marquet: Supervision. Anne Giersch: Conceptualization, Methodology, Resources, Writing - Review & Editing, Supervision, Funding acquisition.

Data Availability:

The data that supported the statistical analyses and figures are available on the Open Science Framework (OSF) at https://osf.io/wrknx/. Raw EEG data and videos are available upon request from the corresponding author.

Code Availability:

The codes used for processing and analyzing behavioural and electroencephalographic data are available on the Open Science Framework (OSF) at: https://osf.io/wrknx/. Matlab 2021b was used for video processing. Matlab 2021b and the EEGlab toolbox 2022.1 were used for EEG data processing. All statistical analyses and figures were performed using R (version 4.3.2).

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3.2. Supplementary Material

Section 1 – Control task

1. Materials and Methods

In the control task, the number of trials per conditions, the equipment, the stimuli were identical to the uni- and multidirectional tasks. Only the way participants answered changed. In this control task, the vibration applied to the forearm was there to warn the participant that the trial started, and that the vibration applied to the wrist would occur after a delay. Participants were instructed to respond as fast as possible to the onset of the wrist vibration by pressing with their dominant hand the central button of a Chronos E-Prime 3.0 response box.

1.1. Analyses of reaction times

Trials corresponding to omission errors (i.e. no response given by the participant), incorrect responses (i.e. pressing the wrong button), and anticipatory response (i.e. RT < 150 ms) were discarded from further analyses.
Out of 120 trials, an average of 4 and 8 anticipated trials per participant were excluded for short and long foreperiods respectively. A total of 112 and 104 trials per participant were included in the following analyses for the short and long foreperiod respectively.

2. Results

2.1. Reaction time

We verified whether we did find the commonly observed temporal prediction indicators (hazard function and sequential effects) on RTs in the control task. To do so, we performed

a two-factor repeated measures ANOVA on RTs with the within-group factors ‘previous foreperiod’ (short vs. long) and ‘current foreperiod’ (short vs. long) (Figure S1.1).

The two-factor ANOVA on RTs revealed a main effect of ‘current foreperiod’ [$F(1,24) = 23.63$, $p = 0.00006$, $\eta^2_p = 0.50$]. This effect reflects a typical hazard function, with RTs being faster when the current foreperiod was long (215 ms ± 54.2) rather than short (236 ms ± 55.2). There was also a main effect of ‘previous foreperiod’ [$F(1,24) = 52.87$, $p = 0.0000002$, $\eta^2_p = 0.69$], with faster RTs when the previous foreperiod was short (216 ms ± 53.9) rather than long (235 ms ± 55.7). We found a significant interaction between the two factors [$F(1,24) = 40.50$, $p = 0.000001$, $\eta^2_p = 0.63$]. Paired t-test confirmed the typical asymmetric sequential effect since RTs were disadvantaged when the previous foreperiod had been long (254 ms ± 52.1), rather than short (218 ms ± 53.3), only when the current foreperiod was short, $t(24) = -8.71$, $p = 0.000000007$.

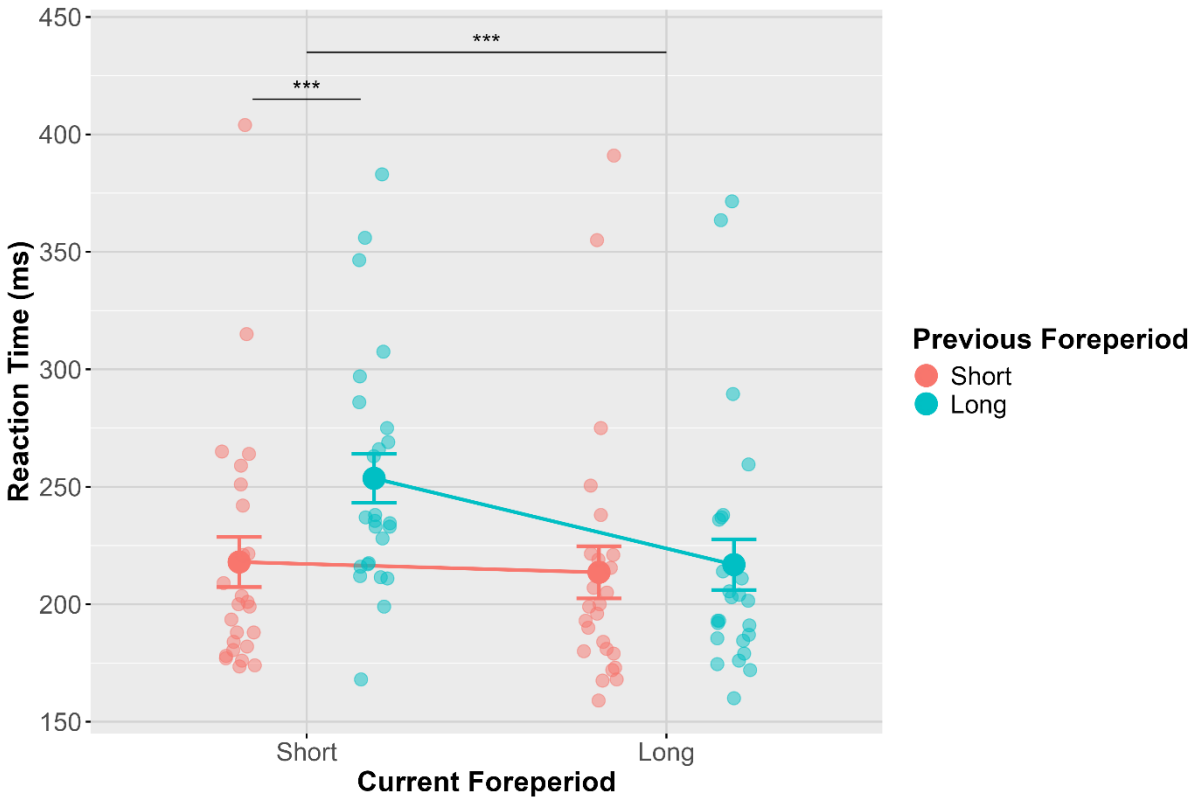

Figure S1.1. RTs in ms on the current trial in the control task, depending on the previous foreperiod. Opaque shapes with error bars show the mean RTs ± SEM, while transparent shapes reflect individual participants' data points in each condition. Statistical significance is denoted by *** for p-values < .001.

2.2. CNV

In the control task, we expected the CNV amplitude (measured before the onset of the second tactile stimulus) to be influenced by sequential effects in case of a short foreperiod. We performed a one-factor ANOVA with the within-group factor 'previous foreperiod' (short vs. long) on the mean CNV amplitude at FCz, Cz and C1 electrodes between 800 and 1000 ms, as for the other tasks (see main manuscript). Since the current foreperiod cannot influence the CNV amplitude in this time window, we did not take this factor into account in our analyses and, as for the other tasks, we grouped all current trials together (i.e. regardless of their foreperiod) (Figure S1.2).

The one-factor ANOVA on the CNV amplitude on current trial revealed a main effect of 'previous foreperiod' [$F(1,21) = 15.44$, $p = 0.0008$, $\eta^2_p = 0.42$], with a more negative CNV amplitude when the previous foreperiod was short (-6.9 u.a ± 5.7) rather than long (-3.5 u.a ± 3.3).

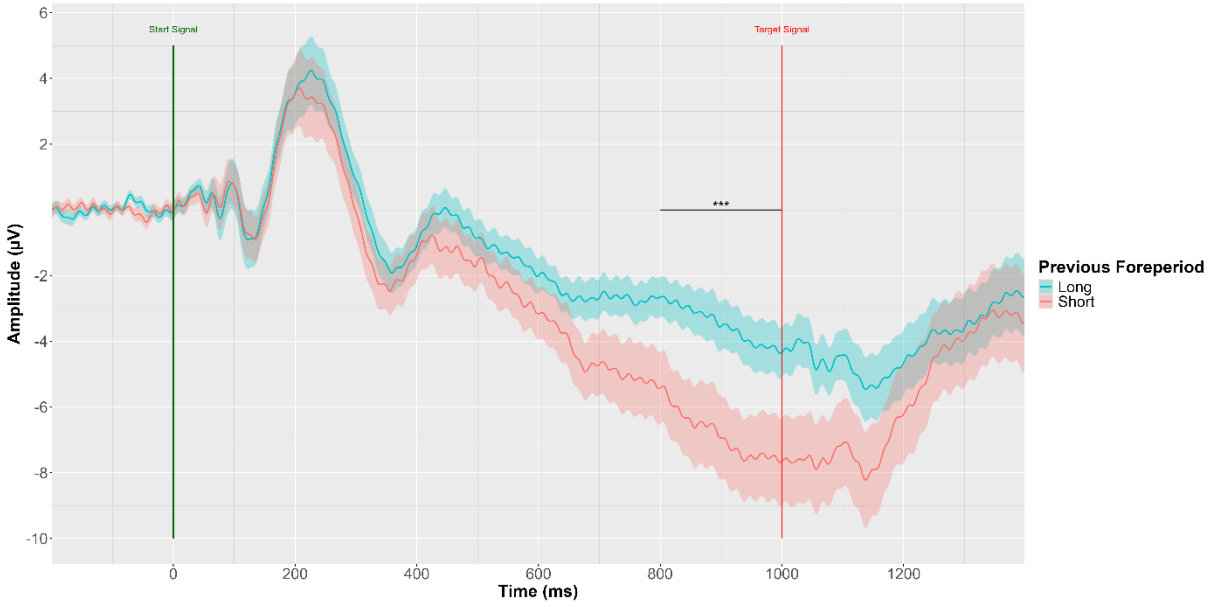

Figure S1.2. CNV amplitudes in µV in the control task, averaged across three electrodes (FCz, Cz, and C1) in all current trials (i.e. regardless of their foreperiod). The shaded area around the lines corresponds to the SEM. 0 ms on the abscissa marks the onset of the start signal (green line), while 1000 ms marks the onset of the target signal at the short foreperiod (red line). Statistical analyses were conducted on the average CNV amplitude in the 800-1000 ms window. Statistical significance is indicated by * for p-values < .05.

3. Conclusion

We did find sequential effects on RTs and on the CNV amplitudes in the control task. These results replicate what is observed in the literature. The results confirm that we are able to observe the usual indicators of temporal prediction abilities on our participants' responses in a typical variable foreperiod task.

Section 2 – Motor tasks

1. Materials and Methods

1.1. Second deceleration point (1000 – 1700 ms)

In trials with a long foreperiod, after 1000 ms in the absence of the target signal at the short foreperiod, participants had to continue their movement until 1700 ms, and perhaps had to update their prediction. The criteria to detect this second deceleration point were identical to those used to detect the first deceleration point, with the difference that the time period of interest for this second deceleration point was in-between the short and the long foreperiod (i.e. from 1000 ms to 1700 ms).

Regarding the deceleration-related parameters of this second deceleration point, we were interested only in its latency and in participants' speed at this point. We were not interested in the deceleration slope between this point and the target signal. Indeed, during the short foreperiod, there is uncertainty about the onset of the target signal, leading participants to automatically rely on information from the previous trial to adjust their deceleration and anticipate the target signal more efficiently on the current trial. Once the moment of the short foreperiod has passed without target signal, participants are certain that the target signal will occur at the long foreperiod. Since we were mainly interested in sequential effects on these deceleration-related parameters, it was not relevant to expect sequential effects on the deceleration slope between the second deceleration point and the target signal at the long foreperiod. At this stage, motor prediction processes appear to be less influential as anticipation is based on the current knowledge.

2. Results

2.1. Reaction times – additional statistics

Effect	DF	F	p-value	η^2_p
Task	(1,24)	19.19	0.0002	0.44
Previous Foreperiod	(1,24)	45.21	0.0000006	0.65
Current Foreperiod	(1,24)	161.41	0.000000000004	0.87
Task * Previous Foreperiod	(1,24)	6.89	0.02	0.22
Task * Current Foreperiod	(1,24)	12.13	0.002	0.34
Previous Foreperiod * Current Foreperiod	(1,24)	22.04	0.00009	0.48
Task * Previous Foreperiod * Current Foreperiod	(1,24)	16.08	0.0005	0.40

Table S2.1: Full results of the three-way ANOVA conducted on RTs in the main manuscript.

Effect	DF	F	p-value	η^2_p
Previous Foreperiod	(1,24)	33.62	0.000006	0.58
Current Foreperiod	(1,24)	75.06	0.000000008	0.76
Previous Foreperiod * Current Foreperiod	(1,24)	55.38	0.0000001	0.70

Table S2.2: Full results of the two-way ANOVA conducted on RTs in the unidirectional task in the main manuscript.

Effect	DF	F	p-value	η^2_p
Previous Foreperiod	(1,24)	4.21	0.05	0.15
Current Foreperiod	(1,24)	105.51	0.0000000003	0.81
Previous Foreperiod * Current Foreperiod	(1,24)	0.70	0.4	0.03

Table S2.3: Full results of the two-way ANOVA conducted on RTs in the multidirectional task in the main manuscript.

2.2. Latency of the first deceleration point

When preparing for the end of the movement, it might have been possible that individuals decelerate earlier when they expect a signal at short foreperiod. If this was the case, we should have observed sequential effects on latencies. This possibility contrasts with the efficiency of the slowing down.

As for the other tasks, the first deceleration point occurred before participants knew if the foreperiod was short or long, and we grouped together all the current trials (i.e. regardless of the foreperiod). We performed one-way repeated measures ANOVAs with the within factor ‘previous foreperiod' (short vs. long) in each task on the dependent variable first deceleration point latencies.

Task	Multidirectional		Unidirectional	
Previous foreperiod	Short	Long	Short	Long
Mean (ms)	519	518	570	583
SD	94.1	82.2	94.3	84.6

Table S2.4: Latencies of the first deceleration point on the current trial as a function of the previous foreperiod, in each motor tasks.

In the unidirectional task, the one-factor ANOVA on the latencies of the first deceleration point showed no main effect of the ‘previous foreperiod’ [$F(1,24) = 2.41$, $p = 0.1$, $\eta^2_p = 0.09$].

The same analysis was conducted in the multidirectional task, and again we found no effect of the ‘previous foreperiod’ on the latencies of the first deceleration point [$F(1,24) = 0.009$, $p = 0.9$, $\eta^2_p = 0.0004$].

In both motor tasks, the latencies of the first deceleration point were not influenced by the previous foreperiod.

The results show that the deceleration always starts at the same moment, whatever the expectation regarding the end of the action, at least at the time corresponding to the short foreperiod.

2.3. Latency of the second deceleration point

As a reminder, the second deceleration point corresponds to the moment when the prediction must be updated because the target signal has not appeared at the short foreperiod. This point is, therefore, only present in trials where the foreperiod is long. We performed one-way repeated measures ANOVAs with the within factor 'previous foreperiod' (short vs. long) in each task on the dependent variable latency of the second deceleration point on the current trial with a long foreperiod.

Task	Multidirectional		Unidirectional	
Previous foreperiod	Short	Long	Short	Long
Mean (ms)	1216	1197	1232	1206
SD	56.7	44.1	84.5	56.0

Table S2.5: Latencies of the second deceleration point on the current trial with a long foreperiod, as a function of the previous foreperiod, in each motor tasks.

In the unidirectional task, the one-factor ANOVA on the latencies of the second deceleration point showed a main effect of the 'previous foreperiod' [$F(1,24) = 4.96$, $p = 0.04$, $\eta^2_p = 0.17$]. Participants started to slow down in anticipation of the onset of the target signal at the long foreperiod faster when the previous foreperiod was long (1206 ms ± 56.0) rather than short (1232 ms ± 84.5).

The fact that the latency is longer when the previous foreperiod was short may correspond to the need to readjust prediction. As a matter of fact, if the previous foreperiod was short, a short foreperiod was expected on the current trial. If the stimulus did not occur at the short foreperiod, the prediction of the signal required to be adjusted before a deceleration was initiated. In contrast, if the previous foreperiod was long, no adjustment was required, and the deceleration could be initiated earlier.

In the multidirectional task, the one-factor ANOVA on the latencies of the second deceleration point showed no main effect of the 'previous foreperiod' [$F(1,24) = 2.33$, $p = 0.1$, $\eta^2_p = 0.09$]. The lack of sequential effects in the multidirectional task matches the lack of sequential effect on the other trajectory parameters.

To compare the two experimental tasks, we performed a two-factor ANOVA on the latencies of the second deceleration point, which revealed no main effect of 'task' [$F(1,24) = 0.90$, $p = 0.4$, $\eta^2_p = 0.04$]. The ANOVA revealed a main effect of the 'previous foreperiod' [$F(1,24) = 9.34$, $p = 0.005$, $\eta^2_p = 0.28$]. The second deceleration point occurred earlier when the previous foreperiod was long (1201 ms ± 50.0) rather than short (1224 ms ± 71.4). No significant interaction between the factors was found [$F(1,24) = 0.17$, $p = 0.7$, $\eta^2_p = 0.007$].

2.4. CNV amplitude – one-factor ANOVA analyses

In the main manuscript, we performed a two-factor ANOVA with the within-group factors 'task' (unidirectional vs. multidirectional) and 'previous foreperiod' (short vs. long) and did not find any interaction between the factors. However, to ensure that we did find sequential effects on CNV amplitude in each task, we also conducted one-factor ANOVAs for each task separately, with the within-factor 'previous foreperiod' influencing the dependent variable 'CNV amplitude' on the current trial. As in previous analyses, the mean CNV amplitude was calculated over a time window of 200 ms, between 800 and 1000 ms, on electrodes FCz, Cz, and C1.

In the unidirectional task, the one-factor ANOVA on the CNV amplitude showed a main effect of 'previous foreperiod' [$F(1,21) = 5.86$, $p = 0.03$, $\eta^2_p = 0.22$], with a more negative CNV amplitude when the previous foreperiod was short (-2.8 u.a ± 4.4) rather than long (-1.2 u.a ± 3.7).

In the multidirectional task, the one-factor ANOVA on the CNV amplitude also showed a main effect of 'previous foreperiod' [$F(1,21) = 4.85$, $p = 0.04$, $\eta^2_p = 0.19$], with a more negative CNV amplitude when the previous foreperiod was short (-2.1 u.a ± 3.7) rather than long (-0.9 u.a ± 2.7).

2.5. CNV amplitude before target signal: short vs. long foreperiod

We verified if the CNV amplitude decreased over time. To verify this, within the same trials, we compared the CNV amplitude in two different time windows: 800-1000 ms (before the onset of the target signal during the short foreperiod) and 1500-1700 ms

(before the onset of the target signal during the long foreperiod). We conducted a two-factor ANOVA with the within-group factors 'task' (unidirectional vs. multidirectional) and 'time window' (800-1000 ms vs. 1500-1700 ms) on the averaged amplitudes from the FCz, Cz, and C1 electrodes.

Effect	DF	F	p-value	η^2_p
Task	(1,21)	2.32	0.14	0.10
Time Window	(1,21)	3.91	0.06	0.16
Interaction	(1,21)	0.30	0.59	0.01

Table S2.6: Full statistical analysis of CNV amplitude averaged across FCz, Cz, and C1 electrodes before the target signal occurrence at short vs. long foreperiod.

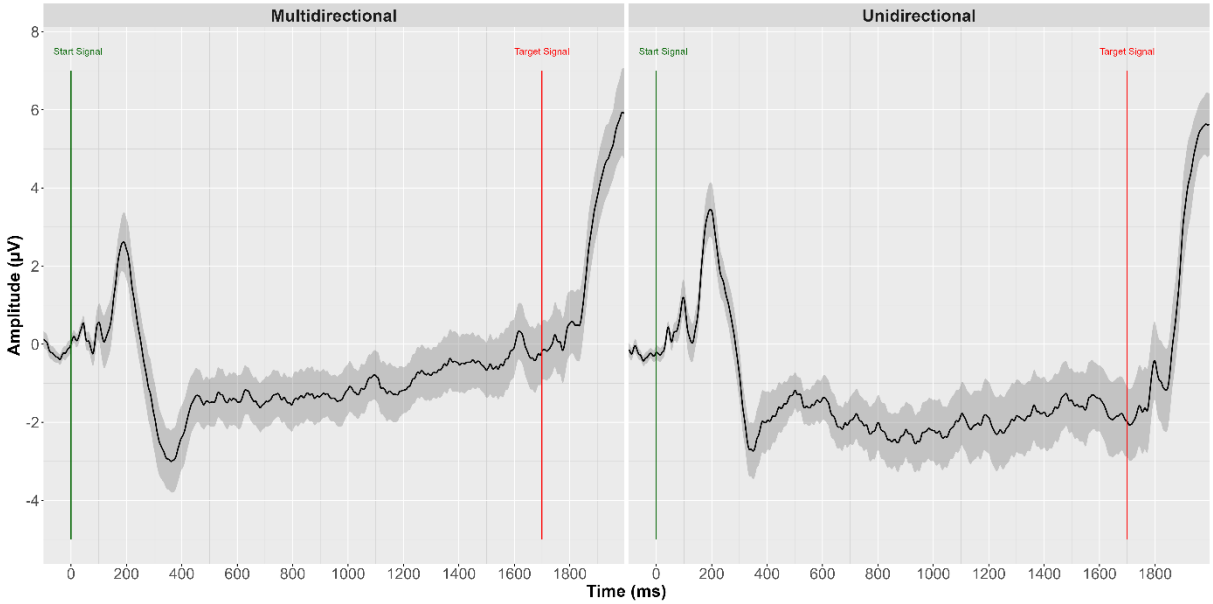

Figure S2.1. CNV amplitudes in µV in multi- and unidirectional tasks averaged across three electrodes (FCz, Cz, and C1) in trials with a long foreperiod. The shaded area around the lines corresponds to the SEM. 0 ms on the abscissa marks the onset of the start signal (green line), while 1700 ms marks the onset of the target signal at the long foreperiod (red line).

The CNV amplitude only tended to decrease during the long foreperiod, which is consistent with findings in the literature (Mento et al., 2013).

2.6 CNV amplitude at long foreperiods: comparison between the two tasks

We tested whether the amplitude of the CNV before the onset of the target signal at the long foreperiod differed between the two motor tasks. To do so, we performed a one-factor ANOVA with the within-group factor 'task' (unidirectional vs. multidirectional) on the averaged amplitudes from the FCz, Cz, and C1 electrodes within the 1500 to 1700 ms time window. The ANOVA revealed no effect of the task factor: [$F(1,21) = 1.72$, $p = 0.2$, $\eta^2_p = 0.08$]. This result confirms that the amplitude of the CNV before the onset of the target signal at the long foreperiod is equivalent across the two motor tasks.

2.7 CNV amplitude at long foreperiods depending on previous foreperiod

At longforeperiods sequential effects are not expected. To demonstrate the absence of sequential effects on CNV amplitude at the long foreperiod, we conducted a two-factor ANOVA with the within-group factors 'task' (unidirectional vs. multidirectional) and 'previous foreperiod' (short vs. long) on the averaged amplitudes from the FCz, Cz, and C1 electrodes within the 1500 to 1700 ms time window.

Effect	DF	F	p-value	η^2_p
Task	(1,21)	1.81	0.19	0.09
Previous FP	(1,21)	2.11	0.16	0.08
Interaction	(1,21)	0.11	0.75	0.005

Table S2.7: Full statistical analysis of CNV amplitude averaged across FCz, Cz, and C1 electrodes within the 1500 to 1700 ms time window, based on the previous foreperiod.

These results align with the literature, where authors typically analyse sequential effects only during the short foreperiod (Mento, 2017).

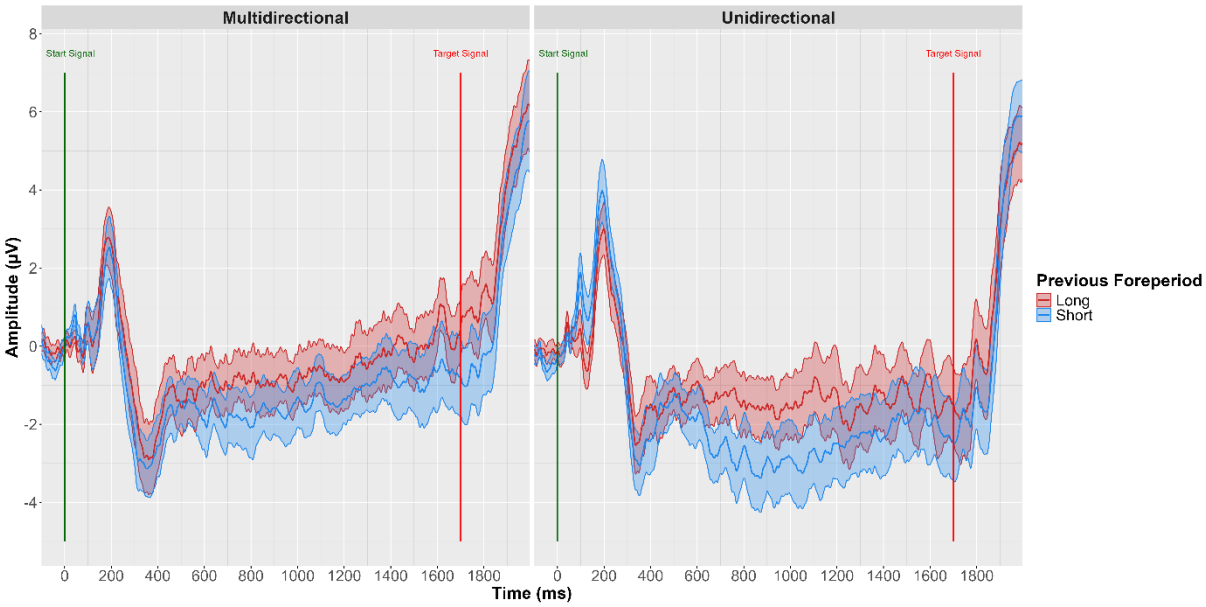

Figure S2.2. CNV amplitudes in µV in multi- and unidirectional tasks averaged across three electrodes (FCz, Cz, and C1) in trials with a long foreperiod. The shaded area around the lines corresponds to the SEM. 0 ms on the abscissa marks the onset of the start signal (green line), while 1700 ms marks the onset of the target signal at the long foreperiod (red line).

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Rappel des résultats principaux de l'étude 1

L'objectif de l'étude 1 est né d'une observation faite lors d'une étude préliminaire, où l'absence d'effets séquentiels sur les TRs dans la tâche multidirectionnelle a suscité des interrogations. Nous avons envisagé que le changement de direction entre essais successifs pouvait être à l'origine de ce résultat, ce qui nous a amenés à explorer l'intégration de la prédiction temporelle dans le contrôle moteur chez des individus neurotypiques.

Nous avons utilisé deux tâches motrices : la tâche multidirectionnelle, où les participants changeaient de direction à chaque essai, et la tâche unidirectionnelle, où ils devaient aller dans la même direction. Les résultats ont confirmé l'absence d'effets séquentiels sur les TRs dans la tâche multidirectionnelle. En revanche, dans la tâche unidirectionnelle nous avons observé des effets séquentiels : au délai court, les participants arrêtaient plus rapidement leur mouvement lorsque le signal cible était également survenu au délai court (plutôt qu'au délai long) à l'essai précédent. Cette dichotomie suggère que les effets séquentiels sur les TRs dans notre paradigme sont bien liés à une prédiction temporelle associée à la commande motrice. Lorsque cette commande change ils disparaissent.

Des effets séquentiels ont également été observés sur les ralentissements anticipatoires de l'arrêt, un indicateur de la préparation de l'arrêt du mouvement. Dans la tâche unidirectionnelle, les participants ralentissaient davantage avant le délai court lorsque le signal cible était survenu au délai court (plutôt qu'au délai long) à l'essai précédent. Là encore ces effets semblent être sous-tendus par une prédiction temporelle liée à la commande motrice puisqu'ils n'ont pas été retrouvés dans la tâche multidirectionnelle.

En revanche, des effets séquentiels indistincts ont été notés sur l'amplitude de la CNV dans les deux tâches. Avant le délai court, l'amplitude de la CNV était plus négative lorsque le délai précédent avait été court (plutôt que long), suggérant que ces effets sont liés à une préparation temporelle indépendante de la commande motrice.

La divergence observée entre l'impact du changement de commande motrice sur les indicateurs comportementaux et EEG nous a conduit à conclure qu'il existe plusieurs mécanismes de prédiction temporelle opérant à la même échelle temporelle.

Objectif de l'étude 2

Dans les protocoles d'attente temporelle, les enfants montrent un bénéfice du passage du temps et des effets séquentiels sur leurs TRs, tout comme les adultes. Cependant, leurs réponses sont généralement moins précises et rapides que celles des adultes. Dans l'étude 1, nous avons montré que la préparation à l'arrêt (ralentissement anticipatoire) et l'exécution de cet arrêt (TR) étaient optimisées lorsque la prédiction associée à l'occurrence du signal cible était intégrée à la commande motrice. L'objectif de notre étude 2 était d'examiner comment s'effectue cette intégration de la prédiction temporelle dans la commande motrice chez les enfants, les adolescents et les adultes.

Chapitre 4. Distinct Maturation of Motor and Sensorimotor Temporal Predictions Throughout Neurodevelopment

Arrouet, A., Marques-Carneiro, E., Marquet, P., Giersch, A. Distinct Maturation of Motor and Sensorimotor Temporal Predictions Throughout Neurodevelopment. En préparation.

4.1. Main Manuscript

Abstract

The existence of both motor and non-motor temporal prediction mechanisms has been suggested in variable foreperiod tasks. This study examines how motor-related temporal predictions evolve throughout neurodevelopment. Participants aged 9 – 24 performed straight-line finger movements until a target signal occurred after either a short or long foreperiod. Sequential effects—how stopping behaviour in one trial affects subsequent trials—were analysed in terms of anticipatory deceleration (motor preparation) and reaction times (motor execution). We used two motor tasks: one where participants changed movement direction between trials (multidirectional task) and another where they repeated the same movement (unidirectional task).

In the unidirectional task, where the motor program is repeated, sequential effects on anticipatory deceleration were observed across all age groups, indicating motor-related temporal prediction is established by age 9. In contrast, sequential effects on reaction times were present in both tasks. Since reaction times reflect motor responses to sensory stimuli, these effects likely represent sensorimotor predictions. The persistence of these effects, even when participants changed movement direction, suggests that sensory-related prediction is not fully integrated into specific motor program during development. This highlights that during neurodevelopment, motor-related temporal prediction matures earlier, while sensorimotor temporal predictions develop later.

Keywords: Temporal Predictions; Sensorimotor Integration; Motricity; Sequential Effects; Neurodevelopment

1. Introduction

Time passes inexorably and influences all mental activities in an incidental way. It enables humans to implicitly adjust their behaviour in various everyday situations. For example, in a game of musical chairs, participants walk or run around a circle of chairs until the music stops. The longer the music plays, the more participants can anticipate its end, allowing them to quickly prepare to halt their movement. However, if the music stops earlier than expected, there is less time to anticipate, making it harder to stop and find a chair. Anticipating the end of a sensory event (such as music stopping) to adjust behaviour (stopping movement) requires both the ability to track the passage of time and to use this sensory prediction to modify motor behaviour (Biederman & Zachary, 1970; Houlihan et al., 1994). One or several of these abilities are likely to be sub-optimal in children, whose motor performance is slower and less accurate than that of adults (Adams & Lambos, 1986; Eckert & Eichorn, 1977; Johnson et al., 2015). Neurodevelopmental maturation may concern sensory temporal prediction, motor optimization, and sensorimotor abilities, i.e. the incorporation of sensory-related temporal predictions into motor programs as children grow older. Here we explore those mechanisms by adding a motor component to a well-known temporal prediction task.

The study of temporal prediction capabilities often uses the variable foreperiod paradigm. In these tasks, a first signal marks the onset of the trial, and after a short or long foreperiod, a target occurs. Participants respond as fast as possible to the target, and their RTs are recorded. According to hazard-based theories, as time passes, the likelihood of the target occuring increases, as does the participants' readiness to respond (Coull, 2009; Luce, 1991; Niemi & Näätänen, 1981). This growing preparedness over time leads to faster RTs after a long foreperiod compared to a short one, illustrating the ‘variable foreperiod effect’ (though other explanations are suggested by Los et al., 2017; Salet et al., 2022). Importantly, in these tasks, participants rely on the passage of time implicitly, without consciously using it to improve their performance (Nobre et al., 2007; Vangkilde et al., 2012). The variable foreperiod effect emerges around 5 years-old (Mento & Tarantino, 2015; Vallesi & Shallice, 2007). Once established, both children and adults show similar time-based influences on performance, indicating comparable variable foreperiod effect across age groups (Elliott, 1970; Ozmun et al., 1989). Such results suggest that temporal

sensory prediction is present early on during neurodevelopment. How it is integrated into motor action and how well this integration occurs are more questionable. It is all the more questionable since adults exhibit better performance than children in variable foreperiod tasks, with faster responses and greater accuracy (Adams & Lambos, 1986; Eckert & Eichorn, 1977; Johnson et al., 2015). These results suggest that some mechanisms of temporal preparation evolve with age. Our previous work has shown that in variable foreperiod tasks, predicting the timing of a sensory stimulus is optimized when it is linked to the motor program (Arrouet et al., submitted). This raises the question of whether the gap in motor performance between children and adults is due to a general improvement in motor precision with age, or whether it is specifically linked to the maturation of sensorimotor integration, where sensory-related temporal predictions are more effectively incorporated into motor programs as children grow older.

Olivier and Rival (2002) investigated whether motor preparation was equivalent across different age groups in a variable foreperiod task. In their experiment, children (aged 6 to 10 years) and adults were required to respond to a target presented after a variable foreperiod by pressing a lever. In some trials, participants could prepare their motor response in advance of the target onset thanks to an explicit cue indicating the side (left or right) and the direction of the response (pushing the lever up or down). Regardless of age, all participants benefited from this explicit cue and improved their RTs compared to trials without the cue. This result shows that children, like adults, can prepare their motor response to improve their RTs when responding to a predictable target. However, the authors observed that the time needed to achieve optimal motor preparation decreased from 2000 ms in younger participants (6 – 8 years) to 500 ms in older ones, indicating an age-related improvement in motor preparation efficiency. Yet, RTs do not directly capture how motor preparation is implemented, as they reflect the outcome of the executed movement rather than the preparatory process itself. As a result, RT may lack the sensitivity to distinguish between mechanisms behind age-related differences of motor preparation. Motor planning typically involves predicting the sensory consequences of an action (Wolpert et al., 1995). It remains thus unclear whether motor adjustments or sensorimotor abilities are the primary contributors to poorer motor performance in young children compared to adults (Eckert & Eichorn, 1977). For instance, when participants are asked to reproduce a rhythm, the variability in inter-tap intervals decreases with age (Drewing et al., 2006; Monier et al., 2019). Achieving good performance in this task

requires precise motor control, which implies accurately predicting the sensory feedback from each tap, as well as an accurate perception of the rhythm (Delevoye-Turrell et al., 2012). Similarly, young children show greater variability when synchronizing taps to a sound, particularly for short intervals (500 and 700 ms) (Monier et al., 2019), indicating that both time precision and the ability to synchronize movements with sensory stimuli improve with development. Research has further demonstrated that sensorimotor learning, especially in infants, shapes time perception more than working memory or motor skills alone (Monier et al., 2019). Sensorimotor abilities are strong predictors of cognitive development (Kertész & Honbolygó, 2023), emphasizing their critical role in neurodevelopment. Consequently, differences in sensorimotor processes could help explain the RT differences observed between children and adults. The hypothesis of a difficulty in sensorimotor integration in children may suggest that the prediction of the sensory consequences of the action is not as straightforward as believed. We use our recently developed procedure to test this idea.

We previously developed a variable foreperiod paradigm, where neurotypicals adults performed a movement during the foreperiod. The task required participants to initiate a straight-line finger movement on a surface after a first signal and stop as fast as possible upon the target signal, which occurred after either a short or long foreperiod. We collected kinematic indicators to assess how participants anticipated the end of their movement (Duque et al., 2017; Woodworth, 1899). Two motor tasks were used: one where participants consistently moved in the same direction on each trial (unidirectional task), and another where they had to change direction on each trial (multidirectional task). In the unidirectional task, repeating the same movement direction allowed participants to maintain their motor program across trials, at least until the short foreperiod. In this task specifically, we found that neurotypical adults used temporal information from the previous trial to adjust their behavioural performance in the current trial (Arrouet et al., submitted).

In the unidirectional task, the trial-to-trial effects (or sequential effects) were as follows: participants slowed down more efficiently before the short foreperiod when the previous foreperiod was also short, compared to when it was long. This benefit of two consecutive short foreperiods was also reflected in the RTs, with participants stopping their movement faster at the short foreperiod when the previous foreperiod was short compared to when

it was long. According to hazard-based theories, these effects rely on a different mechanism than the variable foreperiod effect, and are driven by the expectation that consecutive trials will be similar (Capizzi et al., 2015; Correa et al., 2006; Tal-Perry & Yuval-Greenberg, 2022; Woodrow, 1914). When a short foreperiod is followed by another short foreperiod (short-short sequence), the expectation is met. However, when a long foreperiod is followed by a short one (long-short sequence), the target occurs earlier than expected, leading to unoptimized motor preparation and slower RTs. These sequential effects were not observed at the long foreperiod, consistent with the typical asymmetry reported in the literature.

In the multidirectional task, where participants had to change direction between trials, sequential effects disappeared. This suggests that in neurotypical adults, motor preparation and execution rely on temporal predictions specifically linked to the exact movement being performed. This result is not surprising for the deceleration of the movement, as it is part of the motor process. If the moment of the deceleration is included in the program, then it cannot influence the next movement if the program is reset. However, RT occur after the sensory stimulus, and is more similar to what is observed in typical protocols. Given that the sensory target signal remained the same across trials, and given the belief that sequential effects are both strong and automatic (Vallesi et al., 2007) it was surprising not to find sequential effects on RT. We interpreted these results as suggesting that the prediction of the target signal is closely integrated with the specific motor program, accounting for both the deceleration and the response to the target. In all the results suggested that sensorimotor integration processes are finely tuned to the precise motor action in neurotypicals adults.

Sequential effects are already present on RT in children by the age of 5 (Mento & Granziol, 2020; Mento & Tarantino, 2015; Park et al., 2023; Vallesi & Shallice, 2007). However, given the slow development of sensorimotor abilities (Chicoine et al., 1992; Gordon-Murer et al., 2021; Viel et al., 2009), it is a question whether this prediction will be as selective in young children. If the sensory-related prediction is selectively attached to the motor program, both kinematic indicators and responses should be sensitive to sequential effects, but only in the unidirectional task. If the sensory-related prediction is not selectively attached to the motor program, then responses should be sensitive to sequential effects in both tasks. Trajectory indicators, on the other hand, are inherently

attached to the motor program and we expected them to be sensitive to sequential effects only in the unidirectional task. Our indicators will also give indication regarding the other literature-driven hypotheses, by allowing us to measure the motor-related variability of the children's gestures.

2. Materials and Methods

2.1. Participants

Group	N	Sex (male/female)	Handedness (right/left)	Age	Education
9 – 12 years	10	3/7	9/1	10.5 ± 1.4	5.4 ± 1.5
13 – 17 years	13	6/7	12/1	14.8 ± 1.5	9.5 ± 1.5
18 – 24 years	12	3/9	11/1	21.9 ± 2.1	16.0 ± 2.0

Table 1. Participants' sociodemographic information. Age and level of education are given as mean ± standard deviation.

Neurological or psychiatric disorders were exclusion criteria. Participants with a history of head injury resulting in loss of consciousness for more than one minute were also excluded. Additionally, the use of medication or drugs affecting the brain represented an exclusion criterion.

All participants (and legal representatives for minors) provided informed written consent. The study was conducted in accordance with the Declaration of Helsinki and received approval from the ethics committee of the Sectoral Research Ethics Committee in Neurosciences and Mental Health from the Integrated University Health and Social Services Center (CIUSSS) of the Capitale-Nationale (Project #2022-2009, NSM_).

2.2. Equipment

The experiment was conducted in a dark, silent room with only the participant and the experimenter being present. Participants sat in front of an empty box measuring 45 cm high, 65 cm wide, and 48 cm deep. They were instructed to place their dominant hand

inside the box, with their fist closed and index finger extended, to perform linear movements in response to tactile stimuli. Precision Micro-Drives© vibro-tactile motors were attached to the upper forearm and wrist of the participant's dominant arm to provide tactile stimuli indicating when to start and stop each movement. These motors were connected to a Chronos E-Prime 3.0 stimulation box, set to a vibration intensity of 3.0 V, with a frequency of 230 Hz. Participants wore a headset to mute the sound of the vibrations. The task was managed using an HP ProDesk 600 G2 SFF computer running E-Prime 3.0. Before beginning the tasks, the box was covered with a thick black material to block any light and prevent participants from seeing inside. To record the trajectories of participants' index fingers inside the dark box, a red LED was attached to their index fingernail, and the movements were captured using a GoPro HERO7 camera positioned at 45 cm of height. The video was recorded with a linear field of view, at a resolution of 120 Hz, and in 16:9 full HD format.

2.3. Procedure

The protocol consisted of three variable foreperiod tasks: two motor tasks and a control task, which was similar to those commonly found in the literature.

In the two motor tasks, participants were instructed to perform a straight-line movement following a 100 ms tactile vibration on the upper forearm (start signal) and to stop as fast as possible following a 100 ms tactile vibration on the wrist (target signal). In both tasks, the target signal could occur either 1000 ms (short foreperiod) or 1700 ms (long foreperiod) after the start signal. Each trial started after a variable inter-trial interval (ITI) ranging from 2000 to 2200 ms. Each task consisted of 192 trials, with 96 trials having a short foreperiod and 96 having a long foreperiod, presented in random order.

The main difference between the two tasks was the type of movement performed. In the multidirectional task, participants changed the direction of their movement on each trial, as if exploring a maze. Like in a maze, movements were limited to horizontal and vertical directions (X and Y axes). In the 'unidirectional' task, participants began each trial from the same position and performed the movement in the same direction each time.

Before starting each task, participants went through a training phase of 18 trials to get familiar with the task. During this training phase, the experimenter made sure participants started their movement with the start signal and stopped with the target signal. The speed of their movements was also checked to ensure they weren't moving too fast, reaching the edge of the box, or too slowly, causing an unsteady movement. The experimenter ensured that all participants moved at similar speeds. If a participant accidentally hit the side of the box, they were instructed to stop moving completely and wait until the next trial. This instruction helped identify those trials as anticipations, allowing them to be excluded from the analysis. It should be emphasized that this means we cannot distinguish between true anticipations and too long movements.

In the third control task, participants pressed a button as fast as possible in response to the target signal. This task was used to verify if our sample showed the usual temporal prediction effects (the variable foreperiod and sequential effects) seen in RT. Since this control task was not directly related to our main research question, the details of its methodology and results are included in Supplementary Material - Section 1.

2.4. Data analysis

We analysed the trajectory of the finger (i.e. of the led) with MATLAB 2021b. We established several criteria to enable the script to identify the indicators defined in the following. The criteria, detailed in the Supplementary Material – Section 2 are the same as those validated and used in Arrouet et al. (submitted).

We captured the participants' motor trajectories and used MATLAB 2021b to analyse the behavioural indicators from the recorded video images. The videos were divided into 192 trials, each lasting 3000 ms. Each trial began with the start signal, indicated by the first tactile vibration on the upper forearm. This was marked in the video by a blue LED inside the box that was lit for 100 ms, corresponding with the duration of the forearm vibration. Similarly, when the target signal occurred (i.e. the second tactile vibration on the wrist), a green LED inside the box was lit for the duration of the wrist vibration.

2.4.1. Stopping Latency (i.e. RT)

We measured participants' stopping latencies, which is the time delay required to halt the movement following the onset of the target signal. In our protocol, stopping latency was treated as the RT. RT is a commonly used measure for evaluating performance in variable foreperiod paradigms. This measure enabled us to observe typical behavioural indicators of temporal prediction abilities (variable foreperiod and sequential effects) in our two motor tasks.

RT was measured as the time between the onset of the target signal and the moment when participants stopped their movement. At the stopping point, the speed of their movement was never exactly zero. If their finger was shaking slightly, the movement was still detected, and the speed, while small, was not zero (see Figure 1). Because of this, we had to set criteria for what counted as 'stopping.' Another challenge was that participants moved at different speeds, so we could not use a single speed limit to define when the movement had stopped. Instead, we used percentages of deceleration rather than specific speed values. To ensure the stopping point was identified accurately, we visually checked each trial for every participant using a graph that showed their speed over time. We confirmed that the stopping point placed by the script matched where common sense would have placed it.

In both motor tasks, the stopping point was identified as the first instance where all predefined criteria (detailed in the Supplementary Material – Section 2) were met. Trials where no points met the stopping criteria were excluded from further analysis. Additionally, if the movement was stopped before or within 150 ms after the onset of the target signal, it was considered an anticipated stop, and such trials were also excluded from further analysis. Trials labelled as 'anticipated' and later excluded included both true anticipations and cases where participants reached the edges of the box. If they hit the box edge before the trial ended, they were told to stop moving before the target signal, and this was considered an anticipated stop.

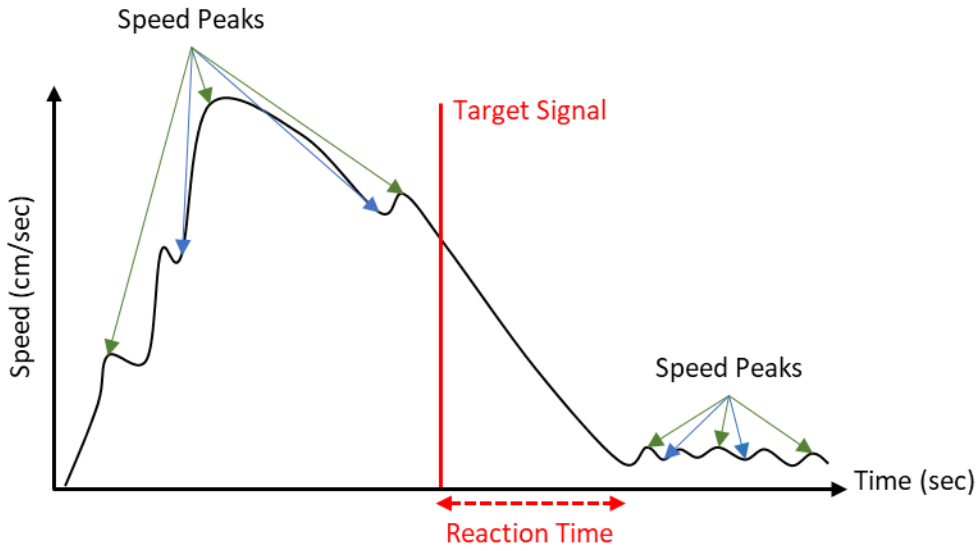

Figure 1. The start signal triggers an initial acceleration. During this phase, speed fluctuates, resulting in peaks. Green arrows show the maximum points, while blue arrows show the minimum points. After 1000 ms (short foreperiod), the target signal occurs (red line on the graph), and the time taken to stop the movement reflects the stopping delay, called RT in our protocol. Although participants stop their movement, small speed peaks caused by tremors can still be detected.

2.4.2. Deceleration Points

Participants began to slow their movement in anticipation of stopping. The initiation of this deceleration was used as an indicator for when stopping started to be prepared (Duque et al., 2017; Woodworth, 1899). Since there are two foreperiods in each task, we consider slowing downs measured before the short foreperiod (i.e. before 1000 ms) and before the long foreperiod (i.e. before 1700 ms). For simplicity, we will refer to these slowing downs as the ‘first deceleration point’ and 'second deceleration point' respectively. The second deceleration point identified between 1000 ms and 1700 ms (long foreperiod) yielded limited additional insights into the results; therefore, we will focus on the initial deceleration point for clarity and conciseness. Additional information and results pertaining to the second deceleration point can be found in the Supplementary Material – Section 2.

Because participants could not predict when the target signal would occur, a first deceleration point was expected in all trials, regardless of the foreperiod length. The

criteria for identifying both deceleration points were identical (except for the temporal window of interest) and consistent across tasks, as detailed in the Supplementary Material – Section 2, and are the same as those validated in Arrouet et al. (submitted). Both deceleration points were defined as the initial slowing down within the window of interest that met all our specified criteria.

We evaluated the efficiency of slowing down in anticipation of the target signal independent of the movement speed by measuring the relative deceleration slope at the first deceleration point. To that aim we calculated the relative speed difference between the first deceleration point and 50 ms prior the onset of the target signal at the short foreperiod, using the following formula: [(speed at the first deceleration point - speed at 950 ms) / speed at the first deceleration point] for all trials. The speed at 950 ms was used instead of the speed at 1000 ms to avoid any potential effect of the onset of the target signal in short foreperiod trials.

By calculating these relative deceleration slopes, we can assess participants' effectiveness in adjusting their movements and facilitate group comparisons while reducing the influence of individual speed variations. These slopes reflect the degree to which participants decrease their speed between two defined moments, before the onset of the target signal.

2.5. Sequential effects index

Sequential effects refer to the observed slowing of RTs at the short foreperiod when it is preceded by a long foreperiod, as compared to when it follows a short foreperiod. To isolate the sequential effect, we calculated the difference in RT between trials with a short foreperiod preceded by a long foreperiod (long-short) and those preceded by a short foreperiod (short-short). This difference was then normalized by dividing it by the sum of the RTs to account for inter-individual variability (like in Foerster & Joos et al., 2024). The formula was as follows:

$$\frac{RT_{long-short} - RT_{short-short}}{RT_{long-short} + RT_{short-short}}$$

A larger positive index indicates more pronounced sequential effects.

2.6. Statistical analysis

		Experimental Task	
Group	Condition	Multidirectional	Unidirectional
9 – 12 years	Short	85	77
	Long	69	61
13 – 17 years	Short	86	93
	Long	77	87
18 – 24 years	Short	92	91
	Long	87	87

Table 2. Number of trials included in the behavioural analyses as a function of the age group, condition and experimental task (total of trials per condition = 96)

Statistical analyses were performed using RStudio (Posit team, 2023). For all indicators, we worked with the median values of each participant. The graphs display the median values of each participant, averaged at the group level. Error bars represent the standard error of the mean (SEM).

For our statistical comparisons, we conducted mixed ANOVAs. If the normality assumption was not met in our datasets, we normalized them prior to performing the ANOVA. We utilized the ‘orderNorm’ function from the ‘bestnormalize’ R package to ensure our datasets followed a normal distribution (Peterson & Cavanaugh, 2020). To maintain a normal distribution while preserving a mean and standard deviation different from 0 and 1, we applied inverse z-scores to our datasets before proceeding with the statistical analysis.

The significance level was set at $\alpha = 0.05$. Partial eta-squared (η^2_p) values are provided as a measure of effect size.

3. Results

3.1. Response phase

3.1.1. Variance of reaction times

The literature suggests that younger individuals are more variable in their RT (Eckert & Eichorn, 1977; Tamnes et al., 2012). We needed to know to which amount age influenced the variability of RTs, because this then required an adaptation of the calculation of RTs effects. Here, we used variance of RT to assess temporal preparation accuracy and examined RT distributions for each participant at both foreperiods across both motor tasks. We looked at variability independent of anticipations and hypothesized that correct (i.e. non-anticipated) responses would be less precise (i.e. more variable) in younger participants compared to older ones.

We performed a three-way mixed ANOVA on participants' variance of RTs with the between-group factor 'age' (9 – 12 years vs. 13 – 17 years vs. 18 – 24 years) and the within-group factors 'task' (unidirectional vs. multidirectional) and 'current foreperiod' (short vs. long) (Figure 2).

The ANOVA revealed a main effect of 'age' [$F(2,32) = 15.44$, $p = .000020$, $\eta^2_p = 0.49$]. Independent t-tests with Bonferroni-corrected p-values revealed that the 9 – 12 age group had significantly more variance in their RTs (29 757 ms² ± 21 524) than both 13 – 17 age group (13 613 ms² ± 11 460), $t(49.8) = 3.85$, $p = .0010$, and the 18 – 24 age group (12 127 ms² ± 12 325), $t(52.3) = 4.11$, $p = .00042$. The latter two groups did not differ from each other, $t(95.8) = 0.63$, $p = 1$. There was also a main effect of 'task' [$F(1,32) = 45.62$, $p = .00000013$, $\eta^2_p = 0.59$], with participants showing greater variability in the multidirectional task (25 621 ms² ± 19 578) compared to the unidirectional task (9 811 ms² ± 8 412). Additionally, a main effect of 'current foreperiod' was observed [$F(1,32) = 33.18$, $p = .0000022$, $\eta^2_p = 0.51$], with participants being more variable in their RTs when the current foreperiod was short (22 655 ms² ± 19 644) rather than long (12 777 ms² ± 12 062).

We found a significant interaction between the 'age' and 'task' factors [$F(2,32) = 3.47$, $p = .043$, $\eta^2_p = 0.18$]. Sub-analyses showed a main effect of age for both tasks, but a post-hoc Tukey HSD test revealed an effect of age in the multidirectional but not in the unidirectional task. In the multidirectional task the 9 – 12 years age group had significantly more variable RTs (42 049 ms² ± 21 947) than both the 13 – 17 (20 335 ms² ± 12 861) and 18 – 24 (17 658 ms² ± 15 484) age groups: $p = .0000057$ and $p = .00000060$, respectively.

Finally, the interaction between the 'task' and 'current foreperiod' factors was significant [$F(1,32) = 18.46$, $p = .00015$, $\eta^2_p = 0.37$]. The post-hoc Tukey HSD test showed that participants were more variable in their RTs at the short foreperiod (34 282 ms² ± 21 287) compared to the long foreperiod (16 961 ms² ± 13 050), but only in the multidirectional task, $p = .0000045$.

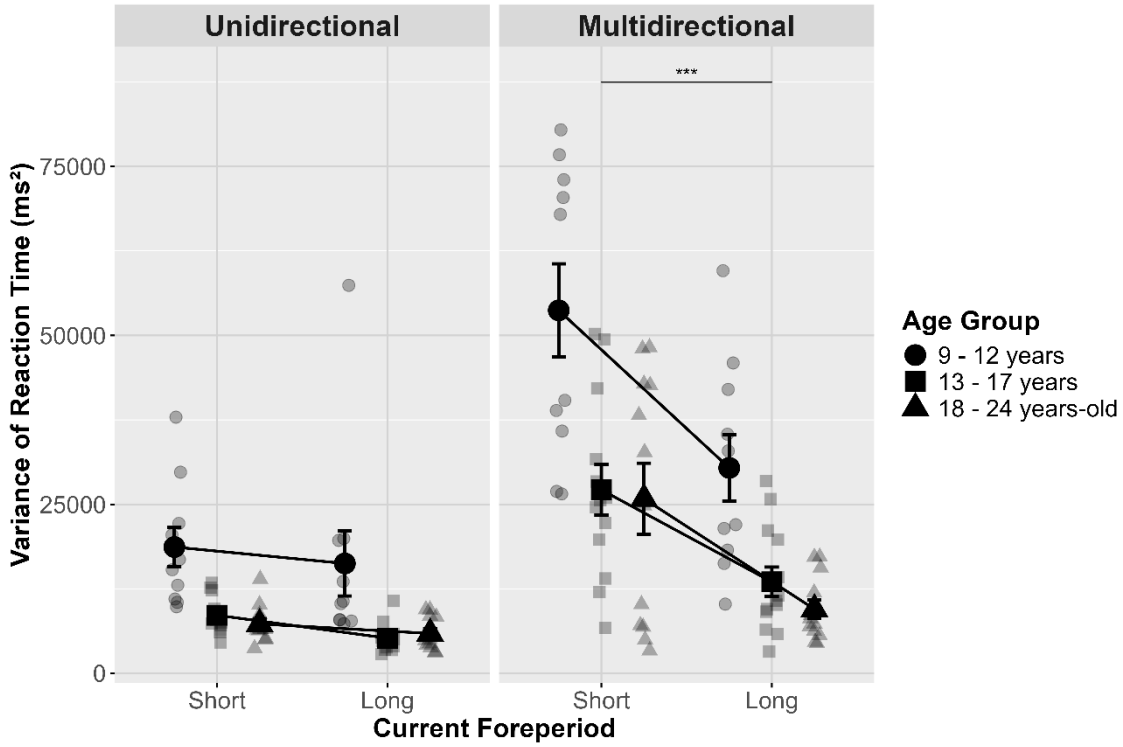

Figure 2. Variance of RTs in ms² shown by the current foreperiod across both motor tasks and three age groups. Opaque shapes with error bars represent the mean variance of RT ± SEM, while transparent shapes reflect individual participants' data points in each condition. Statistical significance is denoted by *** for p-values < .001. The significance bar indicates the interaction effect between task and current foreperiod, with participants

showing greater RT variability at the short foreperiod than at the long one, only in the multidirectional task.

3.1.2. Reaction times

We examined how previous and current foreperiods affected RTs across three different age groups in two motor tasks. The aim of this analysis was to verify the typical indicators of temporal prediction abilities on RTs, such as the decrease in RTs with longer foreperiods (the variable foreperiod effect) and the increase in RTs when a long foreperiod is followed by a short one (sequential effects). We also explored whether these effects are differently influenced by key neurodevelopmental age stages. We conducted a four-way mixed ANOVA on participants' RTs with the between-group factor 'age' (9 – 12 years vs. 13 – 17 years vs. 18 – 24 years) and the within-group factors 'task' (unidirectional vs. multidirectional), 'previous foreperiod' (short vs. long), and 'current foreperiod' (short vs. long) (Figure 3).

The four-way ANOVA on RTs revealed a main effect of 'age' [$F(2,32) = 6.46$, $p = .0040$, $\eta^2_p = 0.29$]. To determine which age group differed from each other, we conducted independent t-tests and applied Bonferroni correction to the p-values. The t-tests revealed that the 9 – 12 age group had significantly slower RTs (439 ms ± 115) compared to both the 13 – 17 age group (389 ms ± 73), $t(125.6) = 3.43$, $p = .0025$, and the 18 – 24 age group (386 ms ± 55), $t(108.3) = 3.79$, $p = .00074$. The latter two groups did not differ from each other, $t(190.6) = 0.31$, $p = 1$. Additionally, a main effect of 'task' [$F(1,32) = 48.77$, $p = .000000065$, $\eta^2_p = 0.60$] was observed, with faster RTs in the unidirectional task (367 ms ± 61) vs. the multidirectional task (438 ms ± 92). The analysis also identified a main effect of 'current foreperiod' [$F(1,32) = 162.37$, $p = .000000000000044$, $\eta^2_p = 0.84$], reflecting the typical variable foreperiod effect, where RTs were faster for a long foreperiod (363 ms ± 58) compared to a short one (442 ms ± 90). Moreover, a main effect of 'previous foreperiod' [$F(1,32) = 43.40$, $p = .00000020$, $\eta^2_p = 0.84$] indicated longer RTs following a trial with a long foreperiod (412 ms ± 90) than with a short foreperiod (393 ms ± 80).

Finally, the three-way interaction between the factors 'task,' 'age,' and 'current foreperiod' was significant [$F(2,32) = 4.53$, $p = .019$, $\eta^2_p = 0.22$]. Independent t-tests with Bonferroni-corrected p-values revealed that the 9 – 12 age group had slower RTs than the

18 – 24 age group in the multidirectional task only, both at the short foreperiod (578 ms ± 114 for the 9 – 12 group vs. 438 ms ± 49 for the 18 – 24 group), $t(24.8) = 5.20$, $p = .00027$, and at the long foreperiod (429 ms ± 65 for the 9 – 12 group vs. 378 ms ± 31 for the 18 – 24 group), $t(57.2) = 3.25$, $p = .038$. The 9 – 12 age group also had slower RTs than the 13 – 17 age group (450 ms ± 72) in the multidirectional task, but only at the short foreperiod, $t(30.4) = 4.47$, $p = .0012$.

A significant interaction was found between the factors 'previous foreperiod' and 'current foreperiod' [$F(1,32) = 32.60$, $p = .0000025$, $\eta^2_p = 0.51$]. A paired t-test confirmed that RTs increased only when the foreperiod in the current trial was short following a previous long foreperiod (462 ms ± 89.0) rather than a short one (422 ms ± 88), $t(70) = -9.64$, $p = .000000000000020$, replicating the typical asymmetrical sequential effect. The three-way interaction between the 'task', 'previous foreperiod', and 'current foreperiod' factors was not significant [$F(1,32) = 0.61$, $p = .41$, $\eta^2_p = 0.020$]. This suggests that the sequential effects on RTs are not significantly different between our motor tasks.

However, the variability of RTs especially in the younger participants may have masked some effects. We conducted an additional analysis. We calculated the index that captures the characteristic RT slowing at the short foreperiod following a long vs. short foreperiod (see Methods section 2.5) to minimize the impact of motor response variability. The two-way mixed ANOVA with the between-group factor ‘age’ and the within-group factor ‘task’ revealed a main effect of the task factor on our sequential effect index: [$F(1,32) = 10.91$, $p = .0020$, $\eta^2_p = 0.25$]. The sequential effect index was two times greater in the unidirectional task (0.06 ± 0.04) compared to the multidirectional task (0.03 ± 0.02). No main effect of the ‘age’ factor was found [$F(2,32) = 0.55$, $p = .59$, $\eta^2_p = 0.030$], nor was there an interaction between the factors [$F(2,32) = 0.10$, $p = .91$, $\eta^2_p = 0.0060$].

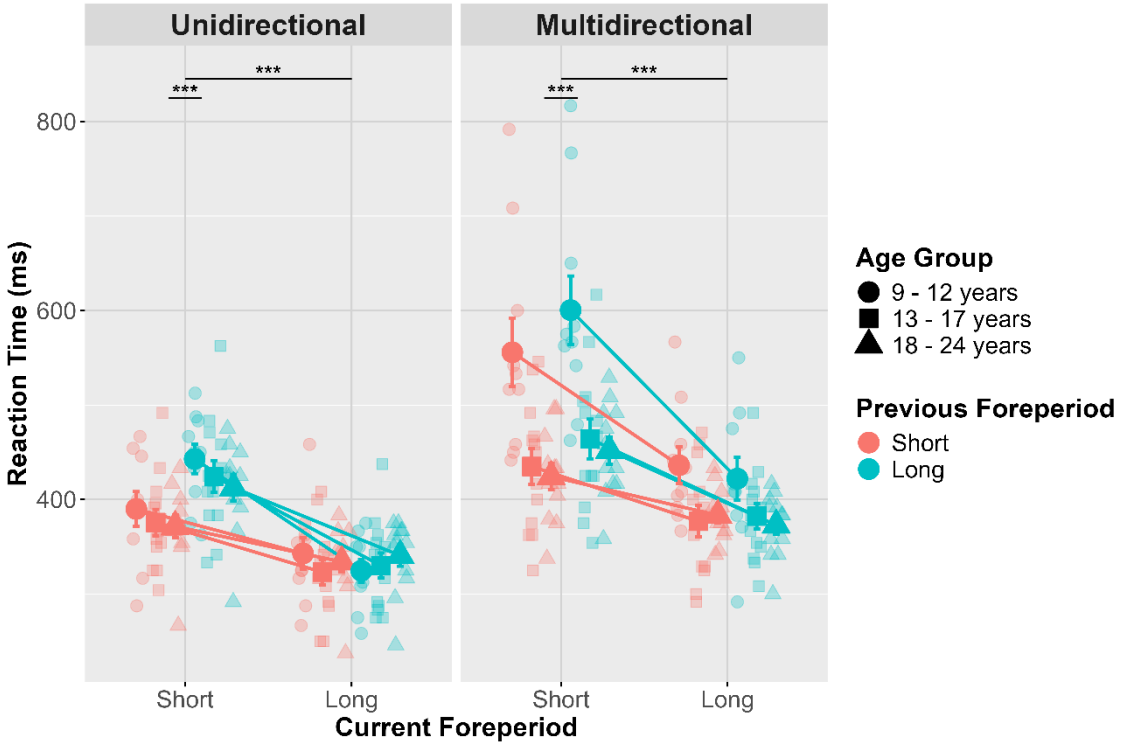

Figure 3. RTs in ms on the current trial for both motor tasks, shown by age groups and the previous foreperiod. Opaque shapes with error bars represent the mean RT ± SEM, while transparent shapes reflect individual participants' data points in each condition. Statistical significance is denoted by *** for p-values < .001. In both panels, the top significance bar indicates the main effect of the current foreperiod factor, while the bar on the far left of the graph shows the interaction effect between the previous and current foreperiod factors, demonstrating that the previous foreperiod influences RT only when the current foreperiod is short.

3.2. Kinematic parameters preceding the response phase

The relative deceleration slope indicates how participants anticipate stopping their movement. This anticipation differs between short and long foreperiod: at the short foreperiod, the onset of the target signal is uncertain, unlike at the long foreperiod. This difference in uncertainty led us to analyse the relative deceleration slopes separately for trials with short and long foreperiods. Results regarding the long foreperiod can be found in the Supplementary Material – Section 2.

3.2.1. Relative deceleration slope at the short foreperiod

Preparing to stop involves predicting when the target signal will occur, and this prediction may or may not be closely linked to the motor program. In adults, during the multidirectional task, where the motor program changes with each trial, the temporal information from the previous motor program is not used to adjust the current movement. However, in the unidirectional task, during which the motor program is repeated from one trial to the next, sequential effects are observed. We aimed to determine if age affects this movement-related temporal prediction differently in our tasks. To do this, we verified the presence of sequential effects on the relative deceleration slope at the short foreperiod, across age groups and both motor tasks.

We conducted a three-way mixed ANOVA on the dependent variable ‘relative deceleration slopes at the short foreperiod’ with the between-group factor 'age' (9 – 12 years vs. 13 – 17 years vs. 18 – 24 years) and the within-group factors 'task' (unidirectional vs. multidirectional) and 'previous foreperiod' (short vs. long) (Figure 4).

The three-way ANOVA on relative deceleration slopes at the short foreperiod revealed a main effect of 'task' [$F(1,32) = 6.72$, $p = .014$, $\eta^2_p = 0.17$], with steeper relative deceleration slopes in the unidirectional task (0.202 ± 0.12) compared to the multidirectional task (0.161 ± 0.09). Additionally, there was a main effect of ‘previous foreperiod’ [$F(1,32) = 4.66$, $p = .038$, $\eta^2_p = 0.13$], showing steeper relative deceleration slopes following a short previous foreperiod (0.191 ± 0.11) rather than a long foreperiod (0.172 ± 0.10). We found no main effect of ‘age’ [$F(2,32) = 0.44$, $p = .65$, $\eta^2_p = 0.030$].

The interaction between the ‘task’ and ‘previous foreperiod’ factors was significant [$F(1,32) = 6.81$, $p = .014$, $\eta^2_p = 0.18$]. A paired t-test confirmed the presence of sequential effects on relative deceleration slopes at the short foreperiod only in the unidirectional task with steeper slope when the previous foreperiod was short (0.220 ± 0.12) rather than long (0.184 ± 0.12), $t(34) = 3.58$, $p = .0010$.

We also found a significant interaction between the ‘age’ and ‘task’ factors [$F(2,32) = 6.12$, $p = .0060$, $\eta^2_p = 0.28$]. To compare the effect of the motor task on relative deceleration slopes within each age group, we conducted a paired t-test with Bonferroni

correction. According to this test, only the 9 – 12 age group showed steeper relative deceleration slopes at the short foreperiod in the unidirectional task (0.258 ± 0.10) compared to the multidirectional task (0.136 ± 0.10) ($t(19) = 5.95$, $p = .000090$). Additionally, independent t-tests with Bonferroni correction revealed that in the unidirectional task, the 9 – 12 age group had steeper relative deceleration slopes compared to the 18 – 24 age group (0.150 ± 0.14, $t(41.8) = 3.03$, $p = .038$). Neither the 9 – 12 nor the 18 – 24 age groups differed significantly from the 13 – 17 age group ($p = .88$ and $p = .85$, respectively).

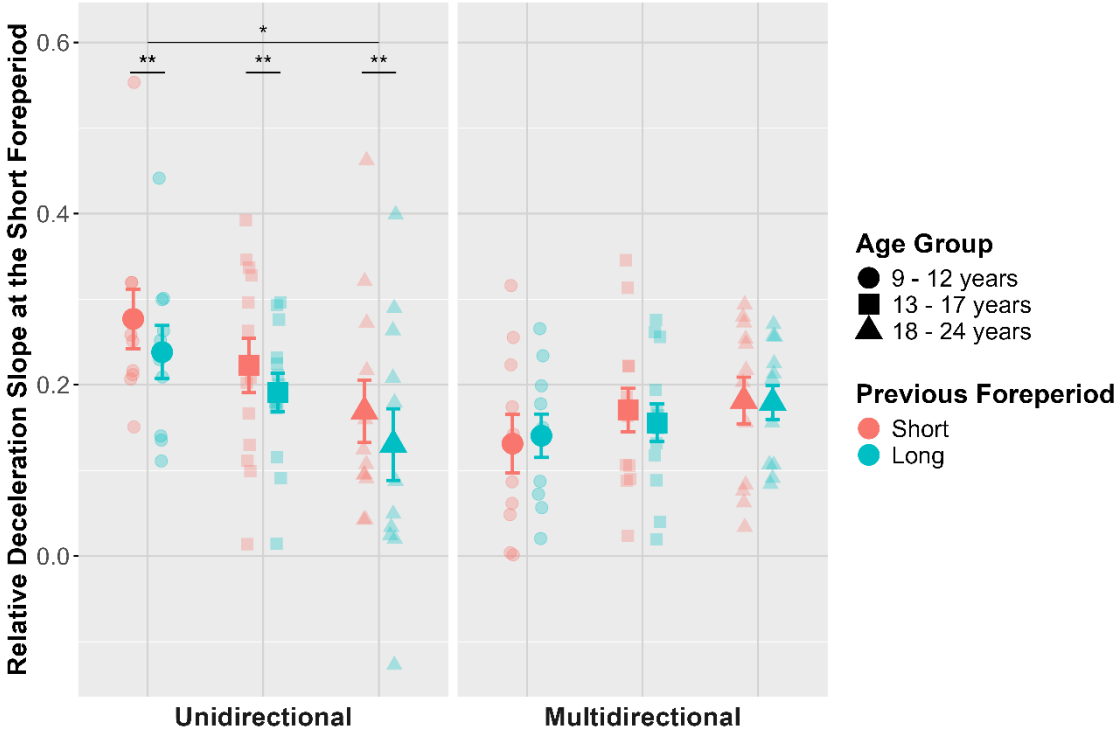

Figure 4. Relative deceleration slopes before the short foreperiod are shown for both motor tasks, across age groups, and depending on the previous foreperiod. Opaque shapes with error bars represent the mean relative deceleration slopes ± SEM, while transparent shapes show individual participants' data points in each condition. Statistical significance is denoted by ** for p-values < .01, and * for p-value < .05. In the unidirectional task, the upper significance bar indicates the age difference between the younger and older groups. The three smaller significance bars below indicate the interaction effect of the previous foreperiod and task factors, showing a sequential effect only in the unidirectional task.

4. Discussion

This study investigates whether the prediction linked to the onset of a sensory signal (sensory-related temporal prediction) influences motor response the same way through neurodevelopment. Specifically, we examined whether sensory-related prediction is as selectively linked to a specific motor program in young individuals as was found in adults (Arrouet et al., submitted). We tested a group of neurotypicals aged from 9 to 24 years in two motor tasks: a unidirectional task, where participants repeated the same movement from trial to trial, and a multidirectional task, where they changed direction each trial. We recorded kinematic indicators (relative deceleration slopes), which reflect the preparation to stop, and response-related indicators (RTs), which represent the execution of the stop. In both cases the prediction of the moment of occurrence of the target could affect performance (deceleration and response to the target), but the response after the target was bound to require more sensory processing. Decelerating before the end of a movement is an inherent part of the motor program, and occurs even in the absence of any target (Woodworth, 1899). In the multidirectional task, the deceleration parameters were expected to reset along with the motor program each time the movement direction changed. The question was to what extent the prediction of the target was embedded within the program itself or remained independent of it, which in the latter case would result in sequential effects. To understand how temporal prediction influence these measures, we examined sequential effects on both indicators. If sequential effects are observed only in the unidirectional task, then it suggests that sensory-related prediction is selectively attached to the motor program. Conversely, if sequential effects are observed in both tasks, it implies that the sensory-related prediction is not tied to a specific motor program

We observed sequential effects on RTs in both motor tasks, with a greater sequential effect in the unidirectional task compared to the multidirectional task. For the relative deceleration slopes, we replicated our previous findings and observed a sequential effect at the short foreperiod solely in the unidirectional task (Arrouet et al., submitted). Sequential effects on our indicators were not age specific. However, we found age-related differences in RT speed and variability, specifically in the multidirectional task. These results align with the literature suggesting that temporal prediction abilities are comparable across age groups, but motor execution is better in older individuals

compared to younger ones, especially when a different motor program is required for each trial. Children (9 – 12 age group) also show less efficient deceleration in the multidirectional task compared to the unidirectional task, for both the first and second relative deceleration slopes (see Supplementary Material – Section 2). This task difference was not observed in the older individuals (13 – 24 age groups). The degraded performance for the multidirectional task in the 9 – 12 age group may be explained by a tendency of children to rely on the immediate prior experience, which can hardly be applied to the multidirectional task, where the gesture has to be changed from trial to trial. A reliance on the immediate prior experience is consistent with the literature. In the variable foreperiod task, both the history of previous trials and the immediate prior experience can influence performance, but children appear to have difficulties using information based on distributions, i.e. on the history of trials over a longer period (Debrabant et al., 2012; Del Popolo Cristaldi et al., 2023; Mento & Granziol, 2020). As children develop, their motor preparation evolves, which could lead to a shift from influences based on immediate prior experience to influences based on distributions, allowing for more precise and faster motor execution (Bender et al., 2005; Flores et al., 2009; Park et al., 2023). These effects do not explain the presence of sequential effects on RTs in the multidirectional task, though.

Across all participants, regardless of the age and the motor task, we observed sequential effects on RTs: participants were slower to stop their movement at a short foreperiod if the preceding foreperiod was long (long-short sequence), compared to when two short foreperiods followed each other (short-short sequence). Even though this sequential effect was stronger in the unidirectional task compared to the multidirectional task, these results contrast with our previous findings in neurotypical adults, where sequential effects on RTs were solely observed in the unidirectional task (Arrouet et al., submitted). In our previous experiment, we interpreted the absence of sequential effects on RTs when the motor program changes as an indication that the prediction of the onset of the target signal (sensory-related temporal prediction) selectively depends on the specific motor program being executed. The current results show that in younger individuals, sensory-related temporal prediction does not yet seem to be fully integrated into a precise motor program. These findings suggest that sensorimotor temporal prediction evolves with age, which support the literature on sensorimotor integration in young individuals. EEG studies on the contingent negative variation (CNV), an event-related potential linked to

sensorimotor temporal expectations (Bender et al., 2005; Flores et al., 2009; Mento & Valenza, 2016; Mento & Vallesi, 2016), have shown significant differences in the cortical structures generating CNV between young individuals and adults. Until at least 13 years of age, CNV primarily originates from the posterior regions as well as the frontal and precentral regions, with no activity observed over the motor cortices. The authors interpret these findings as indicative of differential maturation rates between sensory and motor systems throughout childhood. The asynchronous maturation of sensory and motor systems may indicate a partial dissociation between these processes during development, suggesting that sensorimotor integration is not yet fully established (Gordon-Murer et al., 2021; Viel et al., 2009). Further support for the ongoing development of sensorimotor integration until late adolescence comes from an experiment by Chicoine et al. (1992), where participants aged 5 to 30 years were trained in a pointing task while being able to see their arm. During the test phase, the participants' arms were masked, removing visual feedback. The absence of visual feedback reduced movements accuracy in all participants, with a significantly more marked decrease in those over 20 years. These results suggest that improved motor control with age could be related to better integration of sensory information into the motor program.

There were still sequential effects on RTs in the group aged 18 – 24 during the multidirectional task. This result could be due to heterogeneity in the maturation of sensorimotor integration within this group, with some participants having fully matured integration while others, being younger, have not yet completed maturation. Sequential effects are highly automatic (Kong et al., 2015; Vallesi et al., 2014) and may persist until sensorimotor integration is fully matured. This persistence in some individuals within the 18 – 24 age group would be sufficient to mask a potential significant difference between age groups in the multidirectional task.

Nevertheless, the older groups demonstrated better motor execution, as evidenced by our observations on RT variability: individuals aged 18 – 24 exhibited less RT variability than those aged 9 – 12, particularly in the multidirectional task. Reduced RT variability reflects more precise stopping and a well-executed motor program. This better motor execution in the 18 – 24 age group is further supported by the RT differences observed at the short foreperiod. In the multidirectional task, children aged 9 – 12 were slower to stop their movement compared to both the 13 – 17 and 18 – 24 age groups. The 50% probability of

the target signal at the short foreperiod creates uncertainty, making optimal motor preparation more difficult, especially for children, whose motor preparation is already hindered by immature sensorimotor integration. In older individuals, more mature sensorimotor integration may facilitate the generation of new motor programs for each trial, ensuring efficient execution.

It is unlikely that the RT results observed in our study are due to an age-related difference in processing speed between the three experimental groups (Kail, 1991; Śmigasiewicz et al., 2021). The only task where we observe a deleterious age effect on RTs is the multidirectional task. In the unidirectional and control tasks, older individuals do not have faster RTs than children. This indicates that the speed at which sensory information are processed, and motor commands are executed, is similar between experimental age groups.

5. Conclusion

To conclude, our results showed that in our motor tasks, the sequential effects on kinematic indicators (relative deceleration slopes) and response indicators (RTs) reveal distinct processes, both influenced by temporal preparation. The sequential effects on relative deceleration before the short foreperiod are observed in the unidirectional but not in the multidirectional task. Those results suggest that motor-related temporal preparation is established by the age of 9, and integrates the preparation for the target (in terms of deceleration). In contrast, sequential effects on RTs are observed on both unidirectional and multidirectional tasks—though weaker in the multidirectional task compared to the unidirectional task. Such sequential effects occur after the sensory signal and are likely driven by sensorimotor temporal preparation, which continues to mature throughout adolescence. This maturation may specifically concern the need to adjust the motor plan according to the sensory signal, i.e. an interaction between sensory and motor processes. The differences in motor performance across our age groups suggest that improved performance with age is linked to the maturation of sensorimotor processes. Our findings may help to study neurodevelopmental disorders, which often involve altered temporal prediction abilities (Foerster & Joos et al., 2024). They raise the question of whether sensorimotor temporal prediction, given its late development, is more vulnerable to

abnormal neurodevelopment (Lencer et al., 2010). This also leads to the exploration of whether alterations in temporal prediction are specifically related to sensorimotor integration, or whether they affect all systems requiring precise timing for accurate execution.

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4.2. Supplementary Material

Section 1 – Control task

1. Materials and Methods

The aim of the control task was to verify that we obtain the usual effects in a typical task. The control task was built exactly like the motor tasks, with the same foreperiods, stimuli, and number of trials, but the participants only reacted to the target. They did not have to perform a movement during the waiting period.

Like in the other tasks, the vibration applied to the forearm (start signal) cued the beginning of the trial. After either a short or long foreperiod, a vibration was applied to the wrist (target signal). Participants were instructed to respond as fast as possible to the onset of the target signal by pressing the central button of a Chronos E-Prime 3.0 response box with their dominant hand.

1.1. Analyses of reaction times

Trials that involved omission errors (no response from the participant), incorrect responses (pressing the wrong button), and anticipated responses (RT < 150 ms) were excluded from further analysis.

Group	Condition	Control Task
9 – 12 years	Short	5
	Long	14
13 – 17 years	Short	3
	Long	13
18 – 24 years	Short	3
	Long	9

Table S1.1. Mean number of trials excluded in the behavioural analyses as a function of age group, condition and experimental task (total of trials per condition = 96)

2. Results

2.1. Reaction times

We examined whether the variable foreperiod effect and sequential effects on RTs in the control task were influenced by the age group. To do so, we performed a three-way mixed ANOVA on RTs with the between-group factor 'age' (9 – 12 years vs. 13 – 17 years vs. 18 – 24 years) and the within-group factors ‘previous foreperiod’ (short vs. long) and ‘current foreperiod’ (short vs. long) (Figure S1.1).

The three-way ANOVA on RTs indicated a significant main effect of the ‘current foreperiod’ [$F(1,32) = 16.92$, $p = .00026$, $\eta^2_p = 0.35$]. This finding aligns with the typical variable foreperiod effect, showing faster RTs when the current foreperiod was long (220 ms ± 50) compared to short (239 ms ± 62). There was also a significant main effect of ‘previous foreperiod’ [$F(1,32) = 24.23$, $p = .000025$, $\eta^2_p = 0.43$], with faster RTs when the previous foreperiod was short (222 ms ± 55) rather than long (237 ms ± 58). We observed a significant interaction between the two factors [$F(1,32) = 73.64$, $p = .00000000083$, $\eta^2_p = 0.70$]. A paired t-test confirmed the asymmetrical sequential effects on RTs, with slower RTs at the short foreperiod only when it was preceded by a long foreperiod (255 ms ± 61) rather than a short one (223 ± 60), $t(34) = -7.55$, $p = .0000000091$. There was no impact of the previous foreperiod when the current one was long, $t(34) = 0.21$, $p = .84$.

There was no main effect of the ‘age’ factor [$F(2,32) = 1.53$, $p = .23$, $\eta^2_p = 0.087$], and no other significant interactions were found.

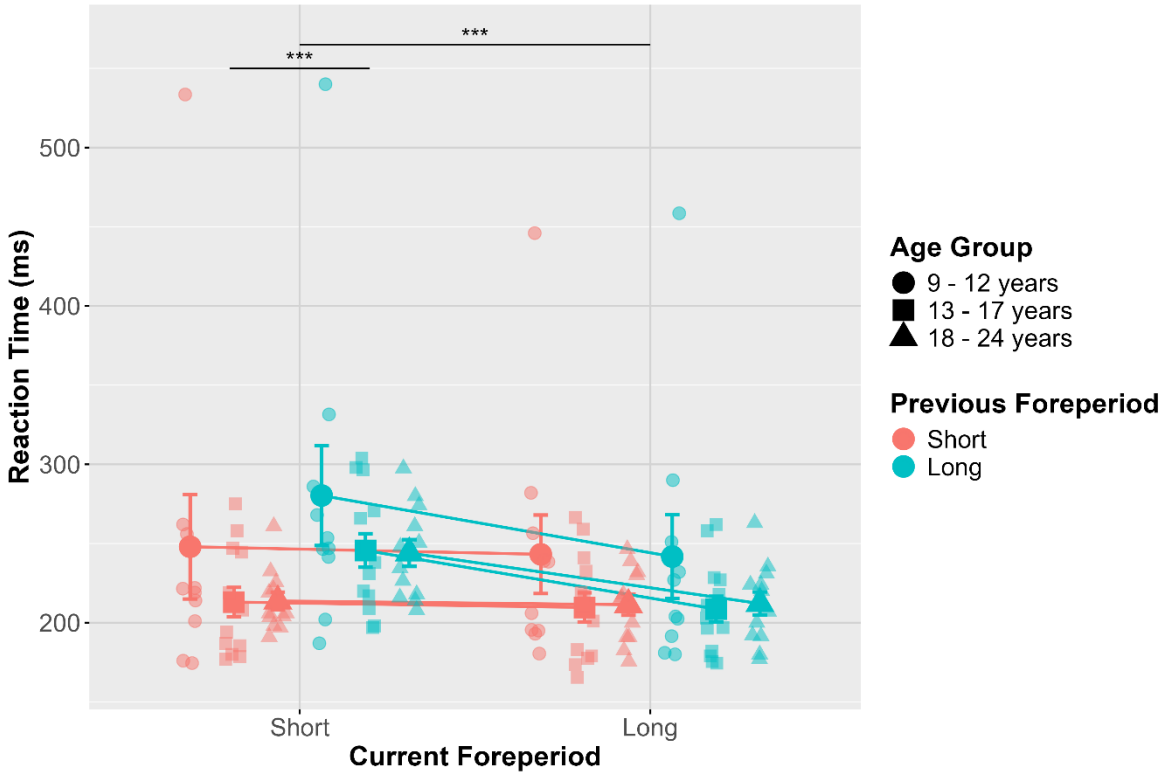

Figure S1.1. RTs in ms in the control task as a function of the current foreperiod, depending on age groups and previous foreperiods. Opaque shapes with error bars show the mean RT ± SEM, while transparent shapes reflect individual participants' data points in each condition. Statistical significance is denoted by *** for p-values < .001. The top significance bar indicates the main effect of the current foreperiod factor, while the bar on the far left of the graph shows the sequential effect and demonstrates that the previous foreperiod influences RT only when the current foreperiod is short.

2.2. Anticipations

We investigated whether anticipated responses during the long foreperiod in the control task were influenced by age (Figure S1.2). We did not analyse anticipated responses at the short foreperiod because there were only very few such anticipations (4 ± 6). To test this, we performed a one-way ANOVA on the number of anticipated responses at the long foreperiod, using 'age' as a between-group factor (9 – 12 years vs. 13 – 17 years vs. 18 – 24 years).

The ANOVA revealed a main effect of 'age' [$F(2,32) = 5.13$, $p = .012$, $\eta^2_p = 0.24$]. Independent t-tests with Bonferroni corrected p-values confirmed that 18 – 24 age group

made less anticipated responses (4 ± 3) than both the 9 – 12 age group (18 ± 13), $t(9.8) = 3.25$, $p = .027$, and the 13 – 17 age group (16 ± 14), $t(13.2) = 2.97$, $p = .032$. The latter two did not differ, $t(20.2) = 0.31$, $p = 1$ (Figure S1.2.A).

A Pearson correlation indicated that the younger the participants, the more anticipated responses ($r(33) = -0.53$, $t(33) = -3.57$, $p = .0011$) (Figure S1.2.B). As in the motor tasks, the number of anticipated responses is significantly correlated with age in the control task.

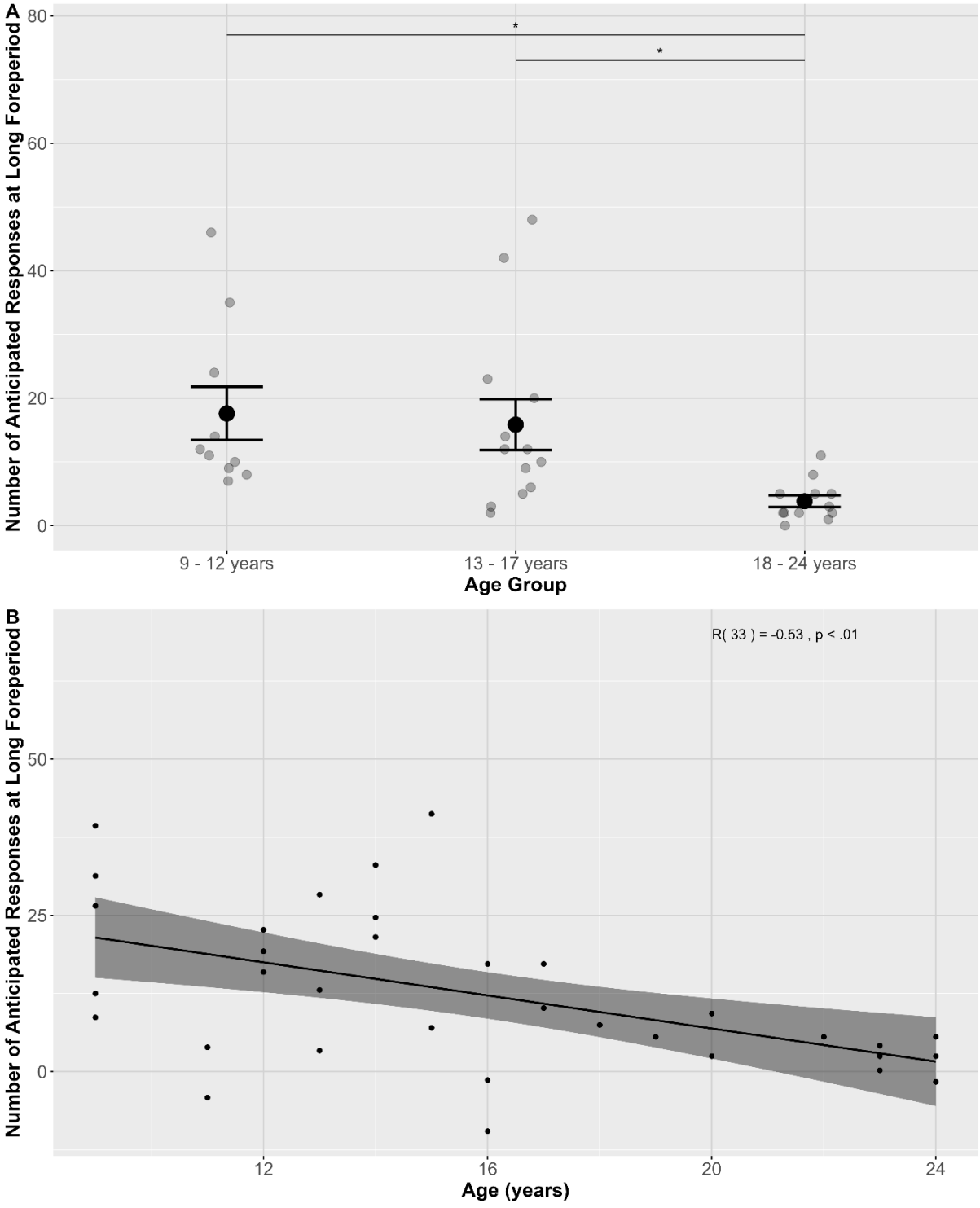

Figure S1.2. Number of anticipated responses at the long foreperiod in the control task, displayed by group (A) and correlated with age (B). Panel A illustrates the differences in anticipated responses across age groups. Opaque symbols with error bars represent the mean number of anticipated responses ± SEM, while transparent symbols show individual participant data points for each condition. Panel B presents the correlation between the number of anticipated responses and participants' age, indicating that older participants

tend to make fewer anticipated responses. The Pearson correlation coefficient is shown on the graph, and statistical significance is marked with * for p-values < .05.

3. Conclusion

In the control task, we observed variable foreperiod and sequential effects on RTs consistently across all age groups, suggesting similar timing abilities among participants (Johnson et al., 2015).

However, we found a significant age effect in the number of anticipated responses at the long foreperiod: the older group made significantly fewer anticipated responses compared to both the middle and youngest groups, which did not differ significantly from each other. Additionally, the number of anticipated responses was correlated with age, as seen in the motor tasks of the main experiment. This result replicates data from the literature (Mento & Granziol, 2020; Vallesi & Shallice, 2007), and further suggests that inhibitory control is still developing in our participants (Constantinidis & Luna, 2019; Vara et al., 2014).

Section 2 – Motor tasks

1. Materials and Methods

1.1 Stopping point

1.1.1 Stopping point criteria in the multidirectional task

The first rule to define a stopping point was that the speed had to decrease by at least 40% from the previous maximum speed. For example, if the maximum speed was 10 cm/sec, the speed at the stopping point had to be 6 cm/sec or lower. While this rule helped identify a significant reduction in speed, it was not enough to confirm that the participants had truly stopped, since their speed could decrease without them stopping entirely. We introduced a second rule to ensure participants were not accelerating again. A stopping point was recognized only if the next two speed peaks were less than twice the speed at the stopping point. In the previous example, if the speed at the stopping point was 6

cm/sec, the next two peaks had to be below 12 cm/sec. However, these two rules alone were not sufficient to confirm a complete stop. Since the participant's finger might tremble slightly, the speed never reached zero. So, instead of using zero as the threshold, we set the stopping threshold based on the speed caused by tremors. To calculate this, we used the median speed peak for each trial (between 0 and 3 seconds), as it reliably represented the tremor speed. Tremor-related peaks were irregular and had many small peaks, which made the median peak a good indicator (see Figure 1 in the main manuscript). The third rule required that the speed at the stopping point must be no more than 1.5 times the median speed peak for that trial. For example, if the stopping point speed was 6 cm/sec, the median peak had to be no higher than 9 cm/sec. The combination of these three rules allowed the program to accurately and consistently identify stopping points, which we verified through visual checks.

1.1.2 Stopping point criteria in the unidirectional task

The criteria for determining stopping points needed to be adjusted for the unidirectional task. In this task, participants moved back to the starting point after stopping, which made the stop less obvious and the stationary period shorter than in the multidirectional task. To address this, we modified the rules: at the stopping point, the speed needed to decrease by at least 30% from the previous maximum speed (compared to 40% in the multidirectional task). The second rule was the same: the stopping point was recognized only if the next two speed peaks were less than twice the stopping point speed. If the stationary period was too short, the following peaks could not be less than twice the stopping point speed, as participants often returned to the starting point quickly, causing the next peak to be the highest of the trial. When this occurred, the stopping point was accepted if the speed at the next peak was at least 50% of the maximum speed for that trial. Finally, to confirm the movement had truly stopped, we added a final rule: the speed at the stopping point had to be no more than 35% of the maximum speed when returning to the starting position. We confirmed that the 35% value was appropriate through visual checks, as a lower percentage would have missed true stopping points.

1.2 First deceleration point (150 – 1000 ms) criteria

For the first deceleration point, we set a time window between 150 and 1000 ms. A minimum of 150 ms is necessary for the brain to process the start signal and send a motor command (Jana et al., 2020). Any deceleration point occurring before 150 ms was considered an anticipation. If the target signal was expected at 1000 ms, slowing down should start before reaching this time. As with the stopping point criteria, we confirmed the consistency of these criteria through visual checks for each trial and participant.

The first criterion was that the speed at the first deceleration point had to be at least 30% of the maximum speed within the specified time window. Visual checks indicated that this 30% threshold was a good balance between avoiding missed cases and false positives. Two additional criteria ensured that participants were decelerating their movement, and not preparing to speed up again. The speed at the next peak had to be at least 10% slower than the speed at the first deceleration point, or the acceleration at the next peak had to be 30% lower than the acceleration at the first deceleration point.

1.3 Second deceleration point (1000 – 1700 ms) criteria

In trials with a long foreperiod, if the target signal did not appear at the short foreperiod (after 1000 ms), participants had to continue their movement until 1700 ms, possibly updating their prediction. The criteria for detecting the second deceleration point were the same as those for detecting the first deceleration point, with the only difference being that the time period of interest for the second deceleration point was between 1000 ms and 1700 ms.

As with the first deceleration point, we calculated a relative deceleration slope in trials with a long foreperiod. To ensure consistency in this calculation, we applied the same logic for the relative deceleration slope related to the second deceleration point, using the following formula: [(speed at the second deceleration point - speed at 1650 ms) / speed at the second deceleration point].

2. Results

2.1 Anticipations

According to the literature and our findings from the control task, younger individuals exhibit more anticipated responses in temporal waiting tasks compared to older individuals (Mento & Granziol, 2020; Vallesi & Shallice, 2007). We wanted to determine if this would also be the case in our motor tasks. The following analysis focuses on trials with a long foreperiod.

We conducted a two-way mixed ANOVA on participants' anticipated responses at long foreperiod with the between-group factor 'age' (9 – 12 years vs. 13 – 17 years vs. 18 – 24 years) and the within-group factor 'task' (unidirectional vs. multidirectional) (Figure S2.1.A).

The two-way ANOVA on anticipated responses revealed a main effect of 'age' [$F(2,32) = 19.63$, $p = .0000027$, $\eta^2_p = 0.55$]. Independent t-tests with Bonferroni-corrected p-values showed that the 9 – 12 age group made significantly more anticipated responses (27 ± 13) compared to both the 13 – 17 age group (10 ± 7), $t(27.7) = 5.43$, $p = .000027$, and the 18 – 24 age group (7 ± 9), $t(33.4) = 5.98$, $p = .0000029$. The latter two groups did not differ from each other, $t(43.3) = 1.36$, $p = 0.54$. No effect of the within-group factor 'task' [$F(1,32) = 0.37$, $p = .55$, $\eta^2_p = 0.012$] was observed.

We found a significant interaction between the two factors [$F(2,32) = 3.58$, $p = .040$, $\eta^2_p = 0.18$]. Paired t-tests revealed that only the 13 – 17 age group showed a significant difference in anticipated responses between the two motor tasks, with more anticipated responses in the multidirectional task (8 ± 7) than in the unidirectional task (12 ± 6), $t(12) = -2.46$, $p = .030$. In contrast, this difference was only a trend in the 9 – 12 age group, $t(9) = 1.88$, $p = .093$, and was not significant in the 18 – 24 age group, $t(11) = 0.09$, $p = .93$.

A Pearson correlation showed that the younger the participants are, the more anticipated responses they make ($r(68) = -0.62$, $t(68) = -6.50$, $p = .000000011$) (Figure S2.1.B). This correlation was not task specific.

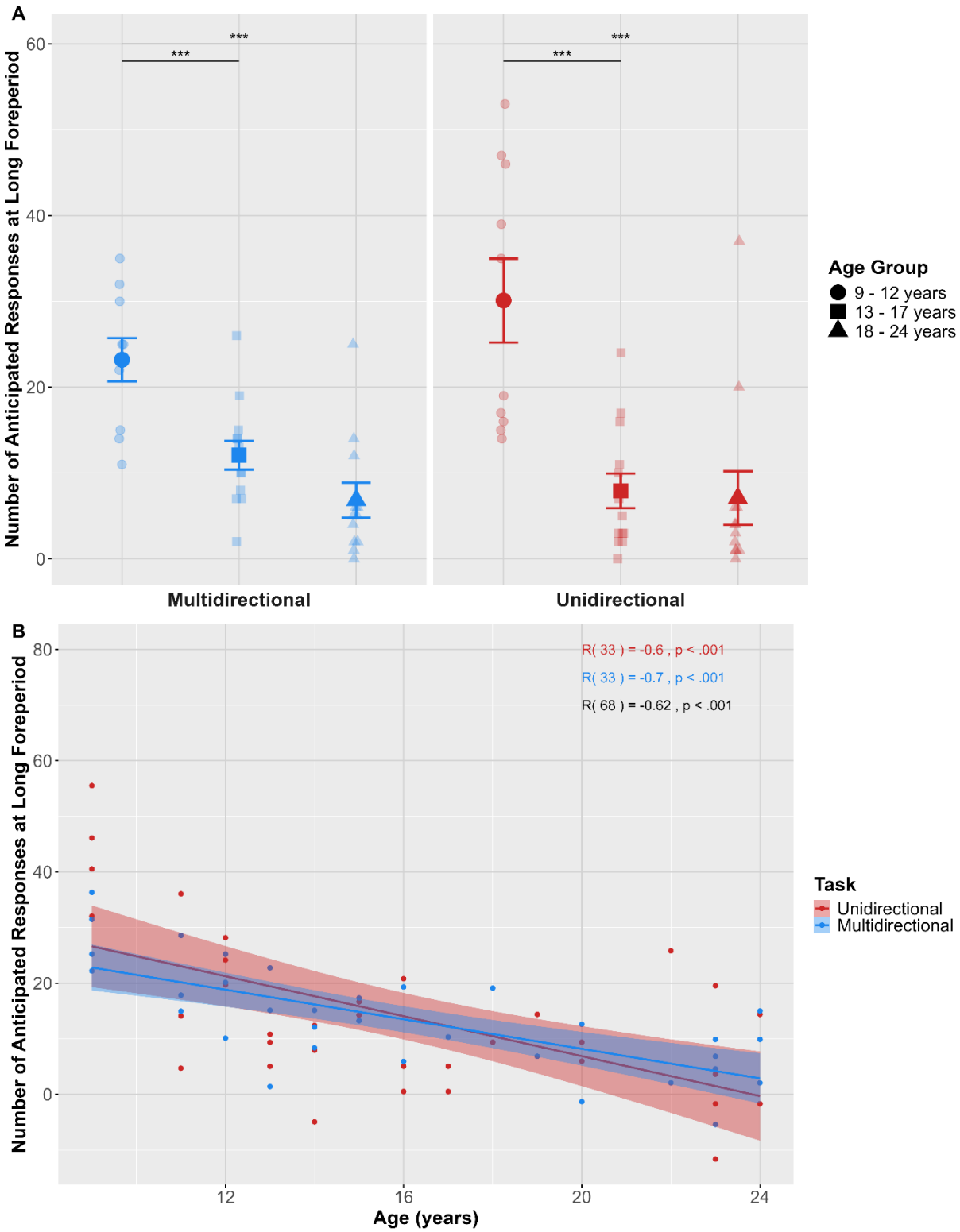

Figure S2.1. Number of anticipated responses across both motor tasks at the long foreperiod, shown as a function of age groups (A) and correlated with age (B). In panel A, opaque shapes with error bars represent the mean number of anticipated responses at the long foreperiod ± SEM, while transparent shapes show individual participants' data points in each condition. In panel B, Pearson correlations are indicated: red for the

unidirectional task, blue for the multidirectional task, and black for both tasks combined. Older participants tend to make fewer anticipated responses at the long foreperiod. Statistical significance is denoted by *** for p-values < .001. In panel A, the upper significance bar indicates the age difference between the youngest and oldest groups, while the bar below indicates the difference between the youngest group and the middle age group.

2.2 Relative deceleration slope at the long foreperiod

We examined whether the deceleration difference observed in children between the unidirectional and multidirectional tasks was also present in the relative deceleration slope at the long foreperiod. In trials with a long foreperiod, the probability of occurrence of the target signal is 100%, which should optimize stop preparation. As a result, the influence of the previous foreperiod is negligible in this analysis. Most importantly, if the probability of the target occurrence is properly accounted for, deceleration efficiency should be similar in both tasks.

We conducted a two-way mixed ANOVA on the dependent variable ‘relative deceleration slopes at the long foreperiod’, with 'age' (9 – 12 years vs. 13 – 17 years vs. 18 – 24 years) as the between-group factor and 'task' (unidirectional vs. multidirectional) as the within-group factor (Figure S2.2).

The two-way ANOVA on relative deceleration slopes at the long foreperiod showed a significant main effect of 'age' [$F(2,32) = 15.88$, $p = .000016$, $\eta^2_p = 0.50$]. Independent t-tests with Bonferroni-corrected p-values revealed shallower relative deceleration slopes in the 18 – 24 age group (0.244 ± 0.06) compared to the 9 – 12 age group (0.337 ± 0.08), $t(36.7) = 4.38$, $p = .00029$, and compared to the 13 – 17 age group (0.290 ± 0.06), $t(46.1) = 2.74$, $p = .026$, while the difference between the 9 – 12 and 13 – 17 age groups tended to be significant, $t(33.3) = 2.34$, $p = .076$. The ANOVA also revealed a main effect of 'task' [$F(1,32) = 22.34$, $p = .000044$, $\eta^2_p = 0.41$], with steeper relative deceleration slopes observed in the unidirectional task (0.319 ± 0.07) compared to the multidirectional task (0.256 ± 0.06). The interaction between the two factors was not significant [$F(2,32) = 1.03$, $p = .37$, $\eta^2_p = 0.060$].

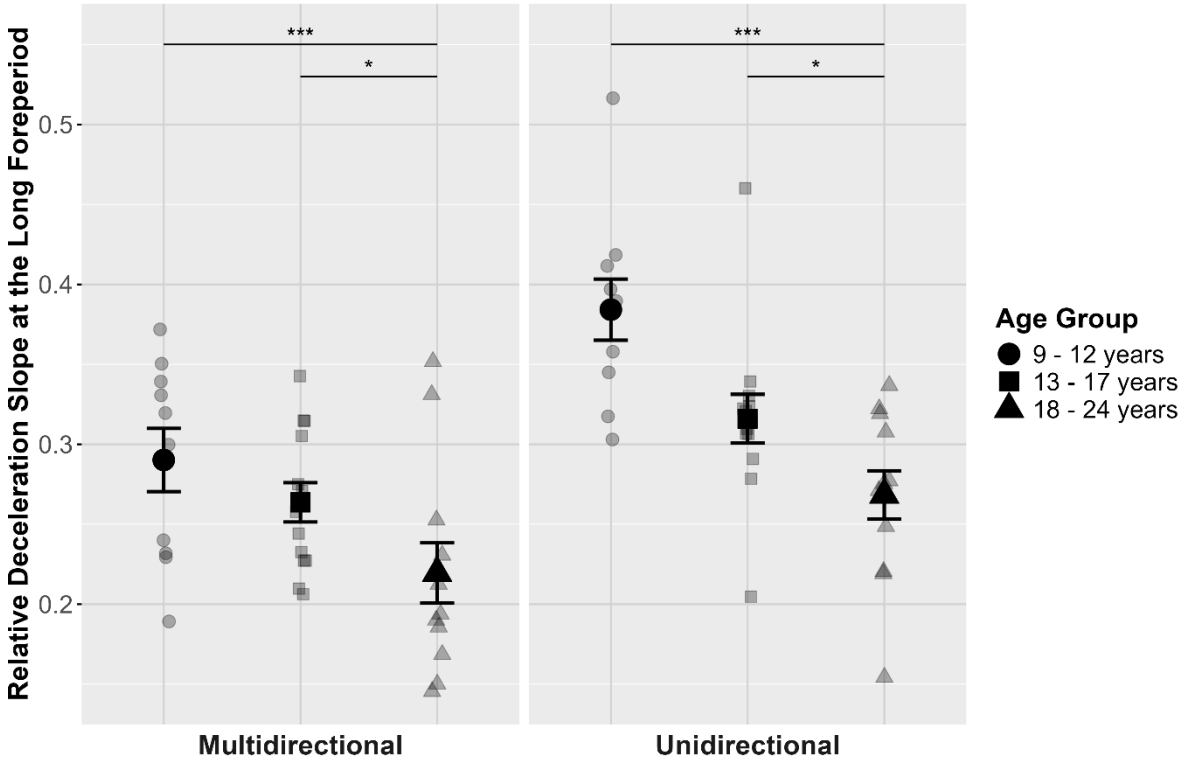

Figure S2.2. Relative deceleration slopes before the long foreperiod are shown for both motor tasks, across age groups. Opaque shapes with error bars represent the mean relative deceleration slopes ± SEM, while transparent shapes show individual participants' data points in each condition. Statistical significance is denoted by *** for p-values < .001, and * for p-value < .05.

3. Discussion

In both motor tasks, older participants exhibit fewer anticipatory responses during trials with a long foreperiod. It might be argued that this analysis also includes trials where participants reached the edges of the box and should be ignored. Nonetheless, the age effect is consistent observed across our two motor tasks, in line with findings from the control task and existing literature (Constantinidis & Luna, 2019; Mento & Granziol, 2020; Vallesi & Shallice, 2007; Vara et al., 2014). Moreover, the cases where participants reached the edges were rare, suggesting that this effect is indeed related to anticipatory responses, even if other types of trials are included. In any case, the results suggest suboptimal motor control.

Regarding the relative deceleration slope in long trials, we note an age effect, with slopes becoming less steep as participants age. These results partially replicate findings on relative deceleration slopes during short foreperiods, where younger participants (aged 9 – 12) demonstrated steeper slopes compared to those aged 18 – 24. Across all participants, relative deceleration slopes were steeper in the unidirectional task than in the multidirectional task. This lack of optimization in deceleration during long trials in the multidirectional task may suggest that motor control continues to mature among participants, even among the older ones, whose control is advanced but not fully optimized.

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Rappel des résultats principaux de l'étude 2

L'objectif de l'étude 2 était d'examiner l'évolution de la prédiction temporelle et son intégration dans la prédiction motrice au cours du neurodéveloppement. Pour cela, nous avons utilisé nos deux tâches motrices, la multidirectionnelle et l'unidirectionnelle, sur une population neurotypique âgée de 9 à 24 ans, afin d'évaluer les effets séquentiels sur des indicateurs liés à la préparation (ralentissement anticipatoire) et à l'exécution (TR) de l'arrêt du mouvement.

Dans la tâche unidirectionnelle, nous avons observé des effets séquentiels similaires entre les enfants, les adolescents et les adultes concernant les ralentissements anticipatoires, ce qui suggère que la prédiction temporelle motrice est présente dès l'âge de 9 ans.

Des effets séquentiels équivalents entre les groupes d'âges ont également été constatés sur les TRs, mais ceux-ci ont été observés dans les deux tâches motrices. Autrement dit, dans les tâches multidirectionnelle et unidirectionnelle, les participants ont tous arrêté leur mouvement plus rapidement au délai court lorsqu'il avait été précédé d'un délai court plutôt que long. Le fait que ces effets séquentiels apparaissent dans les deux tâches, bien qu'ils soient de moindre amplitude dans la tâche multidirectionnelle, suggère que la prédiction de l'occurrence du signal cible n'est pas complètement intégrée à un programme moteur précis chez nos participants. Cela indique que leurs capacités d'intégration sensorimotrice ne sont pas encore complètement mature. Concernant notre groupe le plus âgé, la persistance des effets séquentiels sur leurs TRs dans la tâche multidirectionnelle pourrait refléter une hétérogénéité dans la maturation des processus sensorimoteurs au sein de ce groupe. Les effets séquentiels, étant robustes et automatiques, pourraient persister chez certains individus, ce qui suffirait à masquer une éventuelle différence significative entre les groupes d'âge dans la tâche multidirectionnelle.

En examinant les ralentissements anticipatoires sans tenir compte des effets séquentiels, nous avons observé qu'avant l'occurrence du signal cible au délai court, seuls les jeunes participants ralentissaient plus fortement en prévision du signal cible dans la tâche

unidirectionnelle par rapport à la tâche multidirectionnelle. La répétition du programme moteur d'un essai à l'autre semble leur permettre de planifier leur mouvement de manière plus efficace dans la tâche unidirectionnelle. En revanche, ce schéma de résultats n'est pas observé chez les participants plus âgés, qui n'ont pas besoin de répéter le même mouvement pour assurer une préparation à l'arrêt optimale.

Concernant l'exécution de l'arrêt, les participants plus âgés se montrent également plus efficaces que les plus jeunes : dans la tâche multidirectionnelle, nous avons noté que la rapidité et la précision de leurs réponses augmentaient avec l'âge. Ces résultats corroborent les données de la littérature, indiquant que le contrôle moteur s'améliore avec l'âge, possiblement en lien avec la maturation des processus sensorimoteurs.

Objectif de l'étude 3

La littérature suggère que des troubles du sens de soi sont déjà présents chez les individus à HR de conversion psychotique. Chez les personnes atteintes de SZ de manière chronique, ces troubles ont été associés à des altérations de la prédiction temporelle. L'intégration des informations sensorielles liées à nos mouvements, c'est-à-dire l'intégration sensorimotrice, participe à la construction du sens de soi, en particulier du soi corporel.

L'objectif de cette étude 3 est d'explorer l'impact de la prédiction temporelle, associée à l'occurrence d'un signal sensoriel, sur les réponses motrices des individus à HR. Cette recherche vise à examiner les processus sous-jacents aux altérations sensorimotrices observées dans la littérature et à approfondir notre compréhension du développement de la psychose dans cette population.

Chapitre 5. Temporal Prediction Tasks Reveal Sensorimotor Alterations in Children and Adolescents at Genetic High Risk for Psychosis

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5.1. Main Manuscript

Abstract

We investigated sensorimotor integration, and especially how sensory temporal prediction is integrated in the motor program, in individuals at high-risk (HR) for psychotic conversion. Participants stopped straight-line finger movements in response to target signal presented after either short or long foreperiods. The moment of occurrence of the target is predicted based on past events, but this influence depends on experimental conditions. Participants changed direction on each trial in the multidirectional task and repeated their movement on each trial in the unidirectional task.

When the direction of the movement changes it requires a different motor program; in this case, response execution should not be influenced by previous sensory information, but it was in individuals at HR, thus suggesting that the response is influenced by a sensory prediction remaining independent of the motor program. Anticipatory deceleration was also affected by previous trials, even at long foreperiods, when the motor program should be optimized whatever the trials history. We suggest that sensory predictions are more dissociated from the motor program in individuals at HR than in neurotypicals, highlighting greater immaturity in sensorimotor processes.

Keywords: Temporal Predictions; Sensorimotor Integration; High-Risk for Psychosis; Motor; Sequential Effect

1. Introduction

Children of individuals with major psychiatric disorders, such as schizophrenia (SZ), bipolar disorder, and recurrent major depression, are at high genetic risk (HR) for developing these conditions. Their risk is 8 to 20 times greater than that of the general population (Le et al., 2020; Maziade, 2017). While this risk is significant, it is not 100%. Currently, there are no markers to differentiate between individuals at HR who will develop a psychiatric disorder and those who will not. Since early intervention can improve prognosis (Kulhara et al., 2008; Maximo et al., 2020; Penttilä et al., 2014), it is essential to identify objective markers of the risk of psychotic conversion. This will help distinguish between individuals at HR who are likely to develop psychiatric conditions and those who will remain unaffected.

Self-related disturbances observed in major psychiatric disorders (Inder et al., 2008; Martin et al., 2018; Parnas & Handest, 2003; Sandsten et al., 2020) are particularly noteworthy, as they may manifest even before the onset of the disorder in individuals at HR (Hartmann et al., 1984; Koren et al., 2020; Madeira et al., 2016; Nelson et al., 2012; Parnas et al., 2011). However, these disturbances are often reported verbally and cannot serve as objective markers. One possibility is to explore timing disorders. Self-disturbances have been linked to temporal perception disorders, which are also present in major psychiatric disorders (Fuchs, 2007; Martin et al., 2014; Moskalewicz & Schwartz, 2020; Vogeley & Kupke, 2007). One advantage is that temporal perception disorders can be quantitatively assessed through experimental methods. Previous research has focused in particular on the passage of time, which appears to be altered especially in SZ (Ciullo et al., 2018; Foerster & Joos et al., 2024; Martin et al., 2017; Vogel et al., 2019) as well as in bipolar disorders (Vogel et al., 2018; Weiner et al., 2019).

The perception of the passage of time can be implicitly assessed experimentally using variable foreperiod tasks (Martin et al., 2017; Niemi & Näätänen, 1981; Nobre et al., 2007; Vangkilde et al., 2012). These tasks involve presenting an initial stimulus, followed by a target after either a short or long foreperiod. According to hazard-based theories, as time progresses, the probability of the target appearing increases, enabling participants to prepare their responses more effectively. This leads to faster reaction times (RTs) at the

long foreperiod compared to the short foreperiod, a phenomenon known as the 'variable foreperiod effect' (Correa et al., 2006; Luce, 1991; Mento, 2017; Vallesi & Shallice, 2007; but see Los et al., 2017; Salet et al., 2022 for an alternative explanation). Research has shown that individuals with SZ who exhibit self-related disturbances do not benefit from the passage of time in the same manner as neurotypicals (Foerster & Joos et al., 2024; Martin et al., 2017). Notably, the previously mentioned studies indicated that individuals with SZ did not demonstrate faster RTs when the target occurred after a long foreperiod compared to a short one. As already emphasized impairments in temporal prediction abilities were mainly observed in individuals with disorders of the sense of self. At the group level, impairments were not always observed (Ciullo et al., 2018; Martin et al., 2017), and it may be necessary to adapt the typical tasks to evidence impairments in individuals at HR. The literature indeed suggested disorders of the sense of self in individuals at HR, but mainly with tasks with an important motor component, or related to bodily boundaries.

Pioneering work by Barbara Fish (1957, 1972) highlighted self-related disturbances in the earliest months of life among children of mothers with SZ. Fish observed a 9-month-old child at HR who systematically inspected the back of a mirror after seeing his reflection. This behaviour was interpreted as a primitive form of self-disturbance, suggesting less well-defined bodily boundaries in children at HR compared to neurotypical peers. Fish (1957) also noted that children at HR aged 4 months did not attend to objects they held in their hands in the same way as their neurotypical counterparts, although they demonstrated equivalent attention to objects in their environment. When touching an object, tactile and visual perceptions are coordinated with proprioceptive information derived from exploratory movements. Inasmuch tactile and proprioceptive information is closely related to the bodily self, this multisensory integration inherently associates the hand touching the object with the self, contributing to the establishment of bodily boundaries and the bodily self (Parnas et al., 2002). Potential dysfunctions in multisensory integration during movements in children at HR may hinder the development of bodily boundaries and contribute to self-related disturbances.

Gamma et al. (2014) investigated multisensory integration and its disturbances during object handling as indicators of the risk of developing SZ in children at HR aged 8

months. The authors observed that children at HR performed worse than neurotypical children when reaching for a cube or transferring an object from one hand to the other. Reaching for an object necessitates coordinating visual and proprioceptive information to build a coherent motor program to achieve the goal of reaching the target object (Edwards et al., 2019). Similarly, transferring an object from one hand to the other requires the integration of tactile and proprioceptive information to adjust movements and coordinate actions between the two hands. These behaviours require not only multisensory integration but also the ability to use sensory information to adjust movements accordingly, which is referred to as sensorimotor integration (Wolpert et al., 1995). Literature indicates that sensorimotor integration may be impaired in individuals at HR, potentially contributing to the motor behaviour disturbances observed in this population (Damme et al., 2021; Poletti et al., 2017, 2019; Poletti & Raballo, 2022). These disturbances include delays in acquiring early motor milestones (e.g., walking, sitting without support), deficits in movement coordination, and challenges in both fine and gross motor skills (Burton et al., 2016; Keskinen et al., 2015). While the aetiology of sensorimotor and motor impairments in psychiatric disorders remains unclear, these disturbances are correlated (Damme et al., 2022; Fattal et al., 2024). Notably, individuals at HR who experienced delays in early motor milestones are more likely to show signs of psychotic experiences and depressive symptoms during adolescence (Damme et al., 2022). Furthermore, models that incorporate both early developmental delays and current sensorimotor alterations offer a more comprehensive explanation for psychotic experiences in adolescence than models that examine these factors in isolation (Fattal et al., 2024).

Damme et al. (2024) investigated these motor disturbances further in individuals at HR. To do so, they employed a task requiring participants to press a key precisely when a vertically moving symbol on a computer screen reached a target. This task presented a challenge, as it required participants to time their key press to coincide with the moment the symbol aligned with the target. Responses were evaluated based on precision, measured by the distance between the symbol and the target. Results indicated that individuals at HR exhibited less precise responses than neurotypicals, particularly at the beginning of the task. However, with practice, their precision gradually approached that of neurotypicals. Notably, a negative correlation was found between improvements in response precision and the severity of positive symptoms; in other words, the more

psychotic symptoms, the less motor precision improved over time. These findings suggest that deficits in motor precision could serve as a promising indicator of the risk of psychotic conversion. However, what 'precision' exactly entails may require further investigation. In Damme's task, motor precision may be influenced by sensorimotor integration capacities, as accurately responding when the symbol overlaps with the target requires the ability to predict when this visual information will become available and to time the motor response accordingly. Sensorimotor processes mature throughout neurodevelopment (Chicoine et al., 1992; Viel et al., 2009). Given that psychoses are neurodevelopmental disorders, we investigate time prediction and its impact on motor responses and sensorimotor integration in individuals at HR. This study aims to further investigate the underlying processes associated with the sensorimotor alterations suggested by the literature and to deepen our understanding of the development of psychosis in individuals at HR.

We previously developed a motor version of the variable foreperiod paradigm (Arrouet et al., submitted). In this task, participants were instructed to initiate a straight-line finger movement on a surface following a start signal and to stop their movement as fast as possible upon the target signal, which appeared after either a short or long foreperiod. Kinematic indicators were collected to evaluate how participants anticipated stopping their movements (Duque et al., 2017; Woodworth, 1899). Two distinct motor tasks were employed: the unidirectional task, where participants consistently moved in the same direction for each trial, and the multidirectional task, where they changed direction on each trial.

In the unidirectional task, the repetition of the same movement direction allowed participants to maintain a consistent motor program across trials. Our previous experiments involving neurotypicals (Arrouet et al., submitted; Arrouet et al., in preparation) demonstrated trial-to-trial (or sequential) effects on kinematic indicators specifically in this task: participants exhibited optimized slowing down before the short foreperiod when the preceding foreperiod was also short, compared to when it was long. According to hazard-based theories, these sequential effects stem from the expectation that consecutive trials will be similar, differentiating them from the variable foreperiod effect (Capizzi et al., 2015; Correa et al., 2006; Mento, 2017; Tal-Perry & Yuval-Greenberg, 2022; Woodrow, 1914). In a short-short sequence, the expectation is met;

however, in a long-short sequence, the target appears earlier than anticipated, leading to suboptimal motor preparation.

There were no sequential effects on kinematic indicators in the multidirectional task. This may have seemed surprising given the supposed automaticity of the sequential effects (Vallesi & Shallice, 2007). However, it is the first variable foreperiod paradigm where participants performed a motor action during the foreperiod and had to change it from trial to trial. The results suggest that sequential effects are specifically linked to motor-based temporal predictions, which are activated when the same motor program is repeated across trials, as seen in the unidirectional task. In a previous work with children, we observed that this motor-related temporal prediction becomes evident in neurotypicals by the age of 9 (Arrouet et al., in preparation). We expect to see no differences in sequential effects on kinematic indicators between neurotypicals and individuals at HR, as these effects are rooted in motor-related temporal predictions that develop early in life. Furthermore, the preservation of simple movement execution in psychosis (Delevoye-Turrell et al., 2007) indicates that this may also hold true for individuals at HR. Vallesi & Shallice (2007) and Droit-Volet & Coull (2016) showed both variable foreperiod and sequential effects, at least after 9 years old, but those tasks did not require a motor action to be executed during the foreperiod. We anticipate differences in how individuals at HR plan their stopping responses compared to neurotypicals. Slowing down in anticipation of the sensory signal is a crucial component of movement planning and may be particularly affected by ineffective sensorimotor integration associated with the motor program. If slowing down is affected, it could lead to variations in motor execution between the two groups, as evidenced by differences in RTs speeds.

In terms of sequential effects on RTs, our previous work found that young neurotypicals exhibited these effects in both motor tasks, i.e. whether they had to change their action direction or not: participants stopped their movements faster at the short foreperiod when the previous foreperiod was also short compared to when it was long (Arrouet et al., in preparation). This effect differed from the one observed in adult neurotypicals, who showed sequential effects on RTs only in the unidirectional task (Arrouet et al., submitted). In adults, the prediction of the target signal is linked to a specific motor program, reflecting precise sensorimotor integration. In contrast, young neurotypicals may not have fully integrated sensory predictions into a specific motor program,

indicating that their sensorimotor integration capacities are still developing. We expect to observe similar immaturity in sensorimotor integration processes among individuals at HR.

2. Materials and Methods

2.1. Participants

Population group	Age group	N	Sex (male/female)	Handedness (right/left)	Age	Education
Neurotypicals	9 – 12 years	10	3/7	9/1	10.5 ± 1.4	5.4 ± 1.5
	13 – 17 years	13	6/7	12/1	14.8 ± 1.5	9.5 ± 1.5
Individuals at HR	9 – 12 years	9	3/6	8/1	11.2 ± 0.8	5.8 ± 0.8
	13 – 17 years	15	8/7	13/2	14.4 ± 1.2	8.5 ± 1.1

Table 1. Sociodemographic characteristics of participants. Age and education level are presented as mean ± standard deviation

The inclusion criteria for neurotypical individuals were as follows: neither they nor any first- or second-degree relatives (parents, siblings) nor more than two third-degree relatives (grandparents, uncles, aunts) had ever received a diagnosis according to the DSM-V (American Psychiatric Association, 2013) related to the SZ spectrum or affective disorders. Additionally, any neurological or psychiatric disorders served as exclusion criteria for neurotypicals. Furthermore, the use of any medication or substances that could impact brain function was considered a valid reason for exclusion.

The inclusion criteria for individuals at HR required that they have at least one first-degree relative with a major psychiatric disorder (SZ, bipolar disorder, or recurrent major depression). However, they must not have had any diagnoses related to the SZ spectrum or affective disorders at the time of their inclusion in the experiment.

Some individuals in the HR group had diagnoses related to psychiatric disorders; however, these were not relevant to the conditions investigated in our study, except for one participant who developed depression between the time of inclusion and the time of testing. A summary of these disorders and the associated medications is provided in the table below.

To ensure that the medications taken by individuals in the HR group did not influence their performance differences compared to neurotypical individuals, we conducted analyses comparing neurotypicals to HR individuals who were not on medication. We confirmed that similar effects were observed when comparing all HR individuals (both medicated and unmedicated) to neurotypicals. For each indicator reported in the results section of the main manuscript and supplementary material, we also performed analyses within the HR group to verify that the medication factor did not impact their performance.

	9 – 12 years	13 – 17 years
Attentional deficits disorder (with or without hyperactivity) (yes/no)	1/8	4/11
Anxiety (yes/no)	0/9	1/14
Specific learning disorders (yes/no)	0/9	1/14
Autism spectrum disorder (yes/no)	0/9	1/14
Depression (yes/no)	0/9	1/14
Unspecified mood disorder (yes/no)	1/8	0/15
Stimulant treatment (yes/no)	3/6	6/9
Alpha-2 adrenergic treatment (yes/no)	1/8	0/15
Antidepressant treatment (yes/no)	0/9	1/14
Atypical antipsychotic treatment (yes/no)	1/8	0/15

Table 2. Clinical conditions in individuals at HR groups

Finally, all participants who had experienced a head injury resulting in loss of consciousness for more than one minute were also excluded from the study.

All participants, including legal guardians for minors, provided informed written consent. The study was conducted in accordance with the Declaration of Helsinki and received

approval from the ethics committee of the Sectoral Research Ethics Committee in Neurosciences and Mental Health at the Integrated University Health and Social Services Center (CIUSSS) of the Capitale-Nationale (Project #2022-2009, NSM_).

2.2. Equipment

The experiment took place in a dark and quiet room, with only the participant and the experimenter present. Participants were seated in front of an empty box that measured 45 cm in height, 65 cm in width, and 48 cm in depth. They were instructed to position their dominant hand inside the box, with their fist closed and index finger extended, to perform linear movements in response to tactile stimuli. Precision Micro-Drives© vibro-tactile motors were attached to the upper forearm and wrist of the dominant arm to deliver tactile signals indicating when to initiate and halt each movement. These motors were linked to a Chronos E-Prime 3.0 stimulation box, calibrated to a vibration intensity of 3.0 V and a frequency of 230 Hz. Participants wore headsets to mask the sound produced by the vibrations. The task was administered using an HP ProDesk 600 G2 SFF computer operating on E-Prime 3.0. Prior to starting the tasks, the box was covered with a thick black material to eliminate any light and prevent participants from seeing inside. To capture the trajectories of the participants' index fingers within the dark box, a red LED was affixed to their index fingernail, and movements were recorded using a GoPro HERO7 camera positioned at a height of 45 cm. The video was filmed with a linear field of view, at a resolution of 120 Hz, and in 16:9 full HD format.

2.3. Procedure

The protocol involved three variable foreperiod tasks: two motor tasks and a control task similar to those typically found in the literature.

In the two motor tasks, participants were instructed to execute a straight-line movement following a 100 ms tactile vibration on the upper forearm (start signal) and to stop as quickly as possible upon receiving a 100 ms tactile vibration on the wrist (target signal). In both tasks, the target signal could appear either 1000 ms (short foreperiod) or 1700 ms (long foreperiod) after the start signal. Each trial commenced after a variable inter-trial

interval (ITI) ranging from 2000 to 2200 ms. Each task included 192 trials, with 96 trials for the short foreperiod and 96 for the long foreperiod, presented in random order.

The primary distinction between the two tasks was the type of movement required. In the multidirectional task, participants altered the direction of their movement with each trial, limited to horizontal and vertical directions along the X and Y axes. In the unidirectional task, participants began each trial from the same location and executed the movement in the same direction.

Prior to each task, participants completed a training phase consisting of 18 trials to familiarize themselves with the procedure. During this training, the experimenter ensured that participants initiated their movements with the start signal and halted with the target signal. The speed of their movements was monitored to ensure that they were neither moving too quickly, which could lead to reaching the edge of the box, nor too slowly, which might result in unstable movements. The experimenter visually verified that all participants maintained similar speeds. If a participant accidentally reached the side of the box, they were instructed to cease movement and wait for the next trial. This instruction facilitated the identification of those trials as anticipations, allowing for their exclusion from the analysis. It is important to note that this procedure prevents us from distinguishing between true anticipations and excessively long movements, though.

In the third control task, participants pressed a button as quickly as possible in response to the target signal. This task was employed to determine whether our sample exhibited the expected temporal prediction effects (including the variable foreperiod and sequential effects) observed in RTs. As this control task was not directly related to our main research question, the methodology and results are detailed in Supplementary Material - Section 1.

2.4. Data analysis

We utilized MATLAB 2021b to analyse the trajectory of the finger (specifically, the LED). Several criteria were established to allow the script to identify the defined indicators, which are detailed in Supplementary Material – Section 2 and are consistent with those validated and applied in Arrouet et al. (submitted).

Participants' motor trajectories were recorded and analysed using MATLAB 2021b to extract behavioural indicators from the video footage. The recordings were segmented into 192 trials, each lasting 3000 ms. Each trial began with the start signal which was visually represented in the video by a blue LED inside the box, which illuminated for 100 ms, corresponding to the duration of the forearm vibration. Likewise, when the target signal occurred, a green LED inside the box was activated for the duration of the wrist vibration.

2.4.1. Stopping latency (i.e. RT)

We assessed participants' stopping latencies, defined as the time taken to cease movement after the target signal has occurred. In our study, stopping latency was treated as RT, which is the widely used measure for evaluating performance in variable foreperiod paradigms. RT allowed us to observe typical behavioural indicators of temporal prediction abilities, such as variable foreperiod and sequential effects, in both motor tasks.

RT was determined as the time interval between the onset of the target signal and the moment participants halted their movement. At the stopping point, the speed of their movement rarely reached zero. If the finger exhibited slight shaking, movement was still recorded, resulting in a small, non-zero speed (see Figure 1). Consequently, we had to establish criteria for what constituted 'stopping.' Another complication arose from the varying speeds at which participants moved, making it impractical to apply a uniform speed threshold to define when movement had ceased. Instead, we utilized percentages of deceleration rather than fixed speed values. To ensure accurate identification of the stopping point, we visually inspected each trial for every participant using a graph displaying their speed over time. We confirmed that the stopping point determined by the script aligned with where it would be reasonably expected to be placed.

In both motor tasks, the stopping point was defined as the first occurrence where all predefined criteria (detailed in the Supplementary Material – Section 2) were satisfied. Trials in which none of the points met the stopping criteria were excluded from subsequent analysis. Additionally, if movement ceased before or within 150 ms of the onset of the target signal, it was classified as an anticipated stop, and these trials were also excluded from further analysis. Trials marked as 'anticipated' and subsequently

excluded included both true anticipations and instances where participants made contact with the edges of the box. If they hit the edge of the box before the trial concluded, they were instructed to stop moving prior to the target signal, which was considered an anticipated stop.

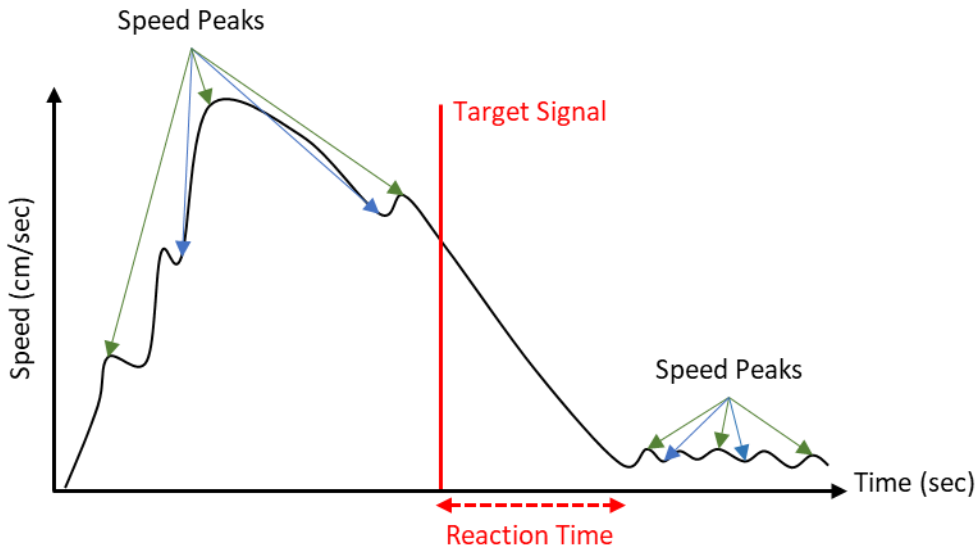

Figure 1. The start signal causes an initial acceleration phase, during which speed varies, leading to fluctuations in peak values. Green arrows indicate the maximum points, while blue arrows represent the minimum points. After 1000 ms (the short foreperiod), the target signal appears (represented by the red line on the graph), and the time taken to halt the movement is referred to as the stopping delay, or RT, in our protocol. Even though participants stop moving, minor speed peaks caused by tremors may still be detected.

2.4.2. Deceleration points

Participants began to decelerate their movements in anticipation of stopping. The onset of this deceleration indicated the beginning of the preparation process for stopping (Duque et al., 2017; Woodworth, 1899). Given that there are two foreperiods in each task, we measured slowdowns occurring before the short foreperiod (i.e., prior to 1000 ms) and before the long foreperiod (i.e., prior to 1700 ms). For simplicity, we will refer to these as the 'first deceleration point' and 'second deceleration point,' respectively.

As participants could not predict the exact timing of the target signal, we anticipated observing a first deceleration point in all trials, regardless of the foreperiod length. The

criteria for identifying both deceleration points were consistent across tasks, aside from the temporal window of interest, as detailed in the Supplementary Material – Section 2, and were the same as those validated in Arrouet et al. (submitted). Both deceleration points were defined as the initial slowing down within the designated time window that met all specified criteria.

We assessed the effectiveness of slowing down in anticipation of the target signal independent of movement speed, by measuring the relative deceleration slope for each deceleration point. We calculated the relative speed difference between the deceleration points and the onset of the target signal using the following formula: [(speed at the first deceleration point - speed at 950 ms) / speed at the first deceleration point] for all trials. The speed at 950 ms was chosen instead of the speed at 1000 ms to eliminate any potential influence from the onset of the target signal in short foreperiod trials. To maintain consistency in the calculation of the relative deceleration slope, we applied the same logic to the second deceleration point, using the formula: [(speed at the second deceleration point - speed at 1650 ms) / speed at the second deceleration point] for trials with a long foreperiod.

By calculating these relative deceleration slope, we can evaluate how effectively participant adjust their movements and compare groups while minimizing the impact of individual speed differences. Relative deceleration slopes indicate how much a participant slows down between two specific points in time, ahead of the target signal.

2.5. Temporal prediction abilities indices

When our descriptive or statistical analyses of raw data indicated a difference in temporal prediction abilities (variable foreperiod and sequential effects), we calculated indices to better isolate these effects (Foerster & Joos et al., 2024).

2.5.1. Variable foreperiod index

The variable foreperiod effect refers to the slowing of RTs at the short foreperiod compared to the long foreperiod. However, this slowing may be affected by sequential effects, which specifically increase RTs at the short foreperiod when it is preceded by a

trial with a long foreperiod. To isolate the true variable foreperiod effect, we calculated the RT difference between short and long conditions for each participant, analysing only trials with the same preceding foreperiod (short-short and long-long on previous and current trials respectively). This difference was then divided by the sum of the RTs to account for inter-individual variability. The formula was as follows:

$$\frac{RT_{short-short} - RT_{long-long}}{RT_{short-short} + RT_{long-long}}$$

A larger positive index indicates a greater variable foreperiod effect.

2.5.2. Sequential effect index

2.5.2.1. Reaction times

For the sequential effects index, we applied a similar approach as for the previous index. According to sequential effects, RTs at short foreperiod are slower when the previous foreperiod was long rather than short. For each participant, we calculated the difference in RT between trials with short foreperiod preceded by a long foreperiod (long-short) and those preceded by a short foreperiod (short-short); our formula was:

$$\frac{RT_{long-short} - RT_{short-short}}{RT_{long-short} + RT_{short-short}}$$

A larger positive index indicates more pronounced sequential effects.

2.5.2.2. Relative deceleration slope at the short foreperiod (1000 ms)

To calculate an index of sequential effects on the relative deceleration slope, we applied the same approach as for the sequential effect index on RTs. It is important to note that a first deceleration point is anticipated in all trials, irrespective of the foreperiod, as participants are unaware of whether the foreperiod is short or long until 1000 ms. Therefore, the current foreperiod was not considered into the calculation of the sequential effect index for this indicator. For each participant, we determined the difference in the

relative deceleration slope when the previous foreperiod was short versus when it was long. Our formula was as follows:

$$\frac{Relative\ deceleration\ slope_{short} - Relative\ Deceleration\ slope_{long}}{Relative\ deceleration\ slope_{short} + Relative\ deceleration\ slope_{long}}$$

A larger positive index indicates greater deceleration at the short foreperiod when preceded by a short foreperiod compared to when preceded by a short foreperiod.

2.5.2.3. Relative deceleration slope at the long foreperiod (1700 ms)

For each participant, we calculated the difference in the relative deceleration slope at the long foreperiod for trials where the previous foreperiod was long (long-long sequence) compared to when it was short (short-long sequence). Our formula was:

$$\frac{Relative\ deceleration\ slope_{long-long} - Relative\ Deceleration\ slope_{short-long}}{Relative\ deceleration\ slope_{long-long} + Relative\ deceleration\ slope_{short-long}}$$

A larger positive index indicates greater deceleration at the long foreperiod when preceded by a long foreperiod compared to when preceded by a short foreperiod.

2.6. Statistical analysis

			Experimental Task	
Population group	Age group	Condition	Multidirectional	Unidirectional
Neurotypicals	9 – 12 years	Short	8	12
		Long	23	30
	13 – 17 years	Short	4	2
		Long	12	8
Individuals at HR	9 – 12 years	Short	12	8
		Long	31	35
	13 – 17 years	Short	3	7
		Long	17	21

Table 3. Mean number of trials excluded in the behavioural analyses (anticipated responses + reaching the edge of the box) based on population group, age group, condition, and experimental task (total trials per condition = 96)

Statistical analyses were conducted using RStudio (Posit team, 2023). For all indicators, we utilized the median values from each participant. The graphs illustrate the average median values at the group level, with error bars representing the standard error of the mean (SEM).

For statistical comparisons, we performed mixed ANOVAs. In cases where the normality assumption was not satisfied, we normalized the datasets before conducting the ANOVA. We employed the 'orderNorm' function from the 'bestnormalize' R package to ensure our datasets conformed to a normal distribution (Peterson & Cavanaugh, 2020). To maintain a normal distribution while allowing for means and standard deviations other than 0 and 1, we applied inverse z-scores to our datasets prior to the statistical analysis.

The significance threshold was established at $\alpha = 0.05$, and partial eta-squared (η^2_p) values were reported as measures of effect size.

3. Results

The results of the control task are detailed in supplementary material. There was no difference between groups in this task on the variable foreperiod or sequential effects. The main effects are observed in the motor tasks, as described hereafter.

3.1. Response phase

3.1.1. Reaction times

We examined how previous and current foreperiods influence RTs as a function of age within our two experimental groups. The goal of this analysis was to determine whether typical indicators of temporal prediction abilities on RTs, such as the reduction in RTs with longer foreperiods (variable foreperiod effect) and the increase in RTs when a long foreperiod is followed by a short one (sequential effects), are differentially influenced by neurodevelopmental stages in experimental groups.

A five-way mixed ANOVA was conducted on participants' RTs with the between-subject factors 'age' (9 – 12 years vs. 13 – 17 years) and 'group' (neurotypicals vs. individuals at HR) and the within-subject factors 'task' (unidirectional vs. multidirectional), 'previous foreperiod' (short vs. long), and 'current foreperiod' (short vs. long) (Figure 2).

The five-way ANOVA on RTs revealed a main effect of 'age' [$F(1,43) = 12.00$, $p = .0010$, $\eta^2_p = 0.22$], with slower RTs for the 9 – 12 age group (438 ms ± 113) compared to the 13 – 17 age group (394 ms ± 82). Additionally, a significant main effect of 'task' was found [$F(1,43) = 96.98$, $p = .0000000000014$, $\eta^2_p = 0.69$], with participants showing faster RTs in the unidirectional task (363 ms ± 75) compared to the multidirectional task (460 ms ± 94). The analysis also revealed a main effect of 'current foreperiod' [$F(1,43) = 196.26$, $p = .000000000000000013$, $\eta^2_p = 0.82$], illustrating the typical variable foreperiod effect, where RTs were shorter for a long foreperiod (365 ms ± 70) than for a short foreperiod (458 ms ± 101). Also, a main effect of 'previous foreperiod' was observed [$F(1,43) = 28.14$, $p = .0000037$, $\eta^2_p = 0.40$], showing that RTs were longer following trials with a

long foreperiod (421 ms ± 101) compared to those with a short foreperiod (402 ms ± 95). No main effect of the ‘group’ factor was found [$F(1,43) = 0.040$, $p = .84$, $\eta^2_p = 0.0010$].

A significant interaction was observed between the 'previous foreperiod' and 'current foreperiod' factors [$F(1,43) = 36.91$, $p = .00000028$, $\eta^2_p = 0.46$]. A paired t-test revealed that RTs increased only when the current trial had a short foreperiod following a previous long foreperiod (477 ms ± 96.6) compared to a short foreperiod (439 ms ± 102.0), $t(93) = -8.64$, $p = .00000000000015$, confirming the typical asymmetrical sequential effect.

The analysis also showed a trend suggesting a significant interaction between the factors of ‘task,’ ‘previous foreperiod,’ and ‘current foreperiod’ [$F(1, 43) = 3.39$, $p = .073$, $\eta^2_p = 0.073$]. Drawing from our earlier findings in neurotypicals (Arrouet et al., submitted; Arrouet et al., in preparation) and the significant two-way interactions observed between the ‘task’ factor and the ‘current foreperiod’ factor, alongside the ‘previous foreperiod’ factor, we proceeded with an additional analysis to isolate the sequential effect. We utilized an index to quantify the characteristic slowing of RTs at the short foreperiod that follows a long foreperiod, as opposed to a short foreperiod (see the Methods section 2.5.2.1). This approach enabled a more precise comparison of sequential effects across tasks, while minimizing the influence of motor response variability in the multidirectional task. The one-way ANOVA, with the within-group factor of ‘task,’ demonstrated a significant effect of the task factor on our sequential effect index: [$F(1, 46) = 23.47$, $p = .000015$, $\eta^2_p = 0.34$]. The sequential effect index was notably higher in the unidirectional task (0.07 ± 0.05) compared to the multidirectional task (0.02 ± 0.04).

The factors age and group also affected performance, as details in the following analyses conducted on RTs.

A significant interaction was observed between the 'task' and 'age' factors [$F(1,43) = 6.92$, $p = .012$, $\eta^2_p = 0.14$]. To examine the differential effect of age across tasks, independent t-tests were conducted with Bonferroni corrections applied to the p-values. The t-tests indicated that the 9 – 12 age group exhibited significantly slower RTs (502 ms ± 105) compared to the 13 – 17 age group (432 ms ± 75), $t(126.1) = 5.05$, $p = .0000031$, specifically in the multidirectional task.

We also found a significant interaction between the ‘age’ and ‘current foreperiod’ factors [$F(1,43) = 6.31$, $p = .016$, $\eta^2_p = 0.13$], and a significant four-way interaction between the factors 'group', 'age', 'task', and 'current foreperiod' [$F(1,43) = 4.11$, $p = .049$, $\eta^2_p = 0.087$]. To verify the age-related differences in the variable foreperiod effect independent of the sequential effects, we calculated the variable foreperiod index, defined as the relative difference in RTs between short and long foreperiods when preceded by the same foreperiod (see the Methods section 2.5.1). A one-way ANOVA was then conducted on this index with the between-subject factor ‘age’ (9 – 12 years vs. 13 – 17 years). The analysis revealed a significant main effect of ‘age’ [$F(1,92) = 7.91$, $p = .0060$, $\eta^2_p = 0.080$], indicating that the 9 – 12 years age group exhibited a greater variable foreperiod effect (0.11 ± 0.08) compared to the 13 – 17 age group (0.07 ± 0.06). As suggested from the graph this effect is unlikely due to an advantage for long foreperiods, but rather explained by slowed RTs at short foreperiods. We thus decomposed the effects of the fourth-level interaction in the ANOVA on raw RTs. Based on graphical data, it appears that the differential effect of age on the current foreperiod is observed specifically in neurotypicals during the multidirectional task.

We analysed the effect of the 'age' and 'current foreperiod' factors within each group and task on RTs. An interaction between 'age' and 'current foreperiod' factors was found only in neurotypicals during the multidirectional task [$F(1,21) = 7.80$, $p = .010$, $\eta^2_p = 0.27$]. Sub-analyses showed a main effect of age for both foreperiods, but a Tukey HSD post-hoc test confirmed that the 9 – 12 age group had slower RTs (578 ms ± 114) compared to the 13 – 17 age group (450 ms ± 72), specifically at the short foreperiod, $p = .0000016$. The age difference was not significant at the long foreperiod, $p = .15$.

All statistical results are available in the Supplementary Material – Section 2.

Finally, we found a trend toward a significant three-way interaction among the ‘group,’ ‘task,’ and ‘previous foreperiod’ factors [$F(1,43) = 3.88$, $p = .056$, $\eta^2_p = 0.083$]. This result suggested a differing effect of the previous foreperiod on RTs between groups in our experimental tasks. However, previous results have shown a high variability of RTs in young individuals (Arrouet et al., in preparation; Eckert & Eichorn, 1977; Tamnes et al., 2012). To understand this effect independently of the variability in RTs that could hinder its significance, we focused on the skewness of the responses at the short foreperiod. We

did not do it for the long foreperiods, as there was no trace of a sequential effect at long foreperiods, t(93) = 0.34, p = .71.

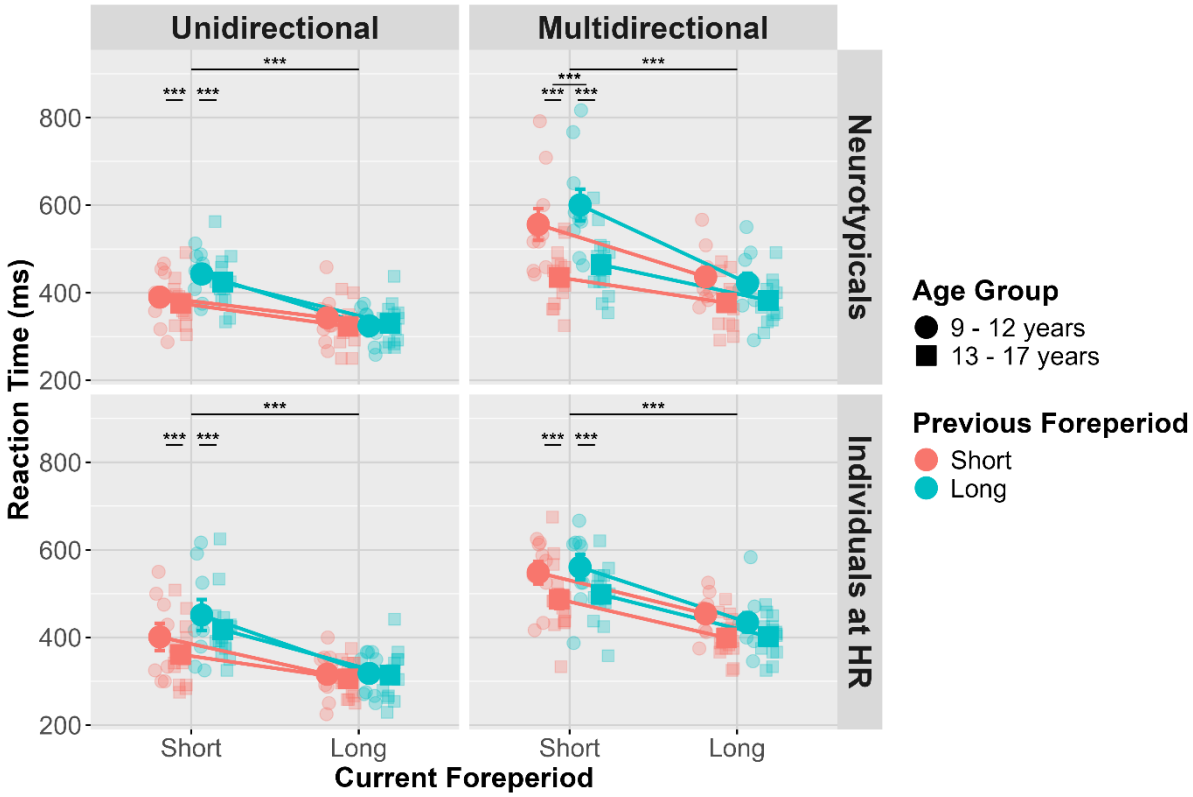

Figure 2. RTs in ms on the current trial in both motor tasks, shown by group, age, and previous foreperiod. Opaque shapes with error bars represent the mean RTs ± SEM, while transparent shapes reflect individual participants' data points in each condition. Statistical significance is denoted by ** for p-values < .01. In all four panels, the upper significance bar represents the main effect of the current foreperiod factor, while the two leftmost bars illustrate the sequential effect, showing that the previous foreperiod affects RT only when the current foreperiod is short. In the panel depicting the neurotypical results for the multidirectional task, the significant bar above the two sequential effect bars highlights that only neurotypicals exhibit an age effect on RT at the short foreperiod in the multidirectional task.

3.1.2. Skewness of the responses at the short foreperiod

This analysis includes all responses at the short foreperiod, both with correct and anticipated responses < 150 ms. Correct responses are those that occur at least 150 ms after the target signal, while anticipated responses considered in the present analysis occur

before this temporal threshold. As noted in the Methods section, anticipated responses include both true anticipations and trials where participants reached the edges of the box. However, such trials were rare, particularly during the short foreperiod.

We conducted a four-way mixed ANOVA on the skewness of all responses at the current short foreperiod, with the between-group factors 'group' (neurotypical vs. individuals at HR) and ‘age’ (9 – 12 years vs. 13 – 17 years) and the within-group factors 'task' (unidirectional vs. multidirectional) and ‘previous foreperiod’ (short vs. long) (Figure 3).

Most effects were trivial and can be attributed to the differences in responses speed among participants, with some participants responding faster while others were slower. All statistical results regarding this analysis are detailed in the Supplementary Material - Section 2.

The purpose of this analysis was to determine whether groups differed on the sequential effects. As a matter of fact the analysis showed a significant interaction between the ‘group’ and ‘previous foreperiod’ factors [$F(1,43) = 4.70$, $p = .036$, $\eta^2_p = 0.10$] (as a reminder this analysis is conducted selectively on trials with a short current foreperiod). Independent t-tests with Bonferroni-corrected p-values showed that when the previous foreperiod was long, individuals at HR exhibited positively skewed responses (0.09 ± 1.4), in contrast to neurotypicals, who showed negatively skewed responses (-0.70 ± 1.5), $t(90.2) = -2.58$, $p = .0031$. This result suggests that individuals at HR are more likely to have slower responses following a long foreperiod, whereas neurotypicals tend to stop their movement faster under the same condition. These effects did not interact with the task factor [$F(1,43) = 0.0090$, $p = .93$, $\eta^2_p = 0.00021$], suggesting that they were similar in the unidirectional and multidirectional tasks.

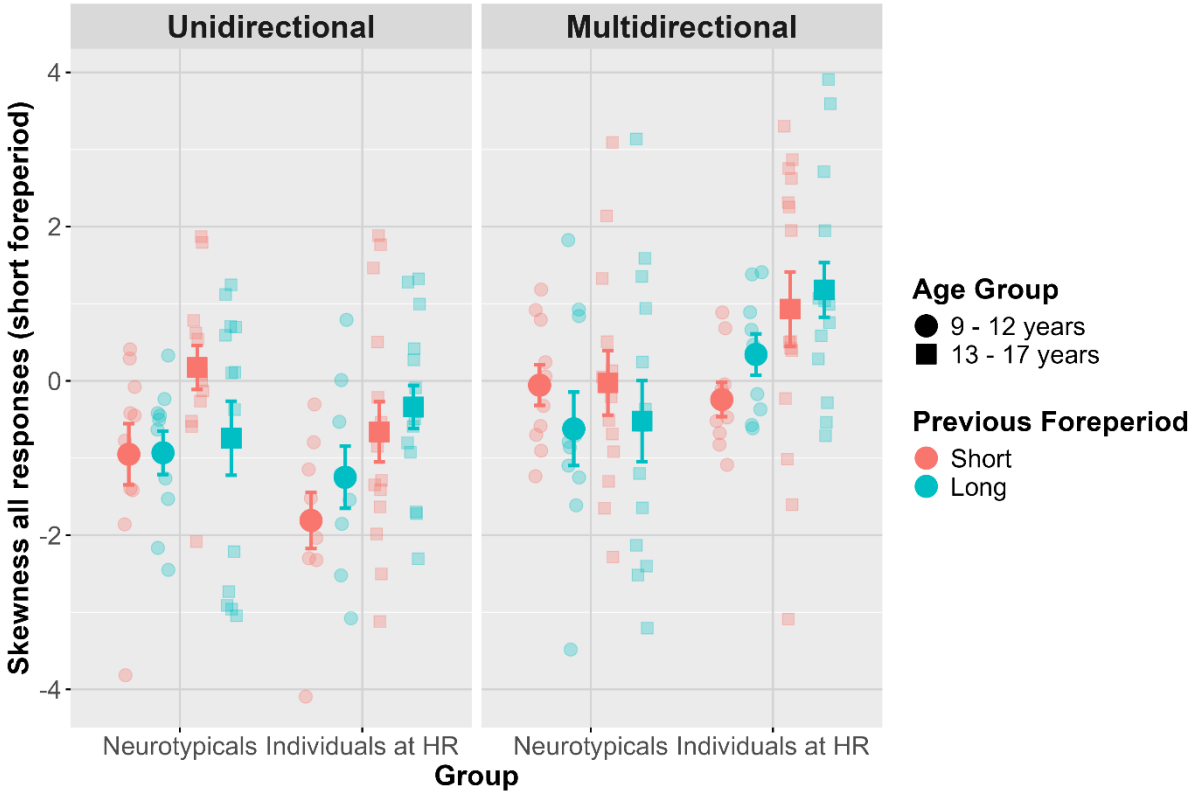

Figure 3. Skewness of RTs, including all trials (both correct and anticipated responses), at the current short foreperiod for both motor tasks, shown by group, age, and previous foreperiod. Opaque shapes with error bars represent the mean skewness of all RTs at the short foreperiod ± SEM, while transparent shapes display individual participants' data points.

3.2. Kinematic parameters

We collected kinematic parameters during the execution of the movement to gain insight into the underlying motor processes involved in preparing to stop. Our objective was to determine whether these motor processes differ between individuals at HR and neurotypicals, particularly in how they cope with motor challenges, such as the necessity to develop a new motor program for each trial due to the change in direction required in the multidirectional task.

3.2.1. Relative deceleration slopes

The relative deceleration slope indicates how participants prepare to stop their movement. This preparation varies between short and long foreperiods: during short foreperiods, the

onset of the target signal is uncertain, with only a 50% chance of occurrence, while at long foreperiods, its onset is guaranteed. This distinction in certainty prompted us to analyse the relative deceleration slopes separately for short and long foreperiods.

3.2.1.1. Short foreperiod (150 – 1000 ms)

Anticipating when to stop involves predicting the onset of the target signal, and this prediction may be integrated into the planification of the movement. In neurotypicals, during the multidirectional task—where the motor program changes with each trial—temporal information from the previous motor program is not used to adjust the current movement. Conversely, in the unidirectional task—where the motor program remains consistent across trials—sequential effects are observed. Furthermore, an age-related effect was observed in neurotypicals: younger participants are particularly affected by the requirement to change direction, as indicated by poorly optimized slowing down in the multidirectional task compared to the unidirectional task. Given these observations, we aimed to determine how sequential effects and age-related differences in movement preparation vary across experimental groups. To explore this, we examined the presence of sequential effects on the relative deceleration slope at the short foreperiod across the two motor tasks and investigated how these effects differ between age groups within our experimental groups.

We conducted a four-way mixed ANOVA on the relative deceleration slope at the short foreperiod, with the between-group factors 'group' (neurotypicals vs. individuals at HR) and ‘age’ (9 – 12 years vs. 13 – 17 years) and the within-group factors 'task' (unidirectional vs. multidirectional) and 'previous foreperiod' (short vs. long) (Figure 4).

Statistics on raw data can be found in Supplementary Material – Section 2, confirming the steepness of deceleration in the unidirectional task (as observed in a previous study). The analysis also showed that individuals at HR had steeper slopes compared to neurotypicals in the 13 – 17 years age group, regardless of the task. Here we report the results related the sequential effects.

An interaction between the ‘previous foreperiod’ and ‘task’ factors was observed [$F(1,43) = 6.0$, $p = .018$, $\eta^2_p = 0.12$]. Paired t-tests confirmed that the previous foreperiod

influenced the relative deceleration slope only in the unidirectional task, with steeper slopes following a short foreperiod (0.25 ± 0.12) compared to a long foreperiod (0.21 ± 0.10), $t(46) = 4.50$, $p = .000047$.

These effects did not interact with the group, but we looked more closely at these results by conducting a three-way mixed ANOVA on the index of the sequential effects on the relative deceleration slopes (see Method section 2.5.2.2.), with the between-group factors ‘group’ (neurotypicals vs. individuals at HR) and ‘age’ (9 – 12 years vs. 13 – 17 years), and the within-group factors 'task' (unidirectional vs. multidirectional).

We found a tendency towards a group effect [$F(1,43) = 3.26$, $p = .078$, $\eta^2p = 0.070$], with a larger sequential effects in individuals at HR (0.10 ± 0.41) than in neurotypicals (0.003 ± 0.29). Additional statistical results are available in the Supplementary Material – Section 2.

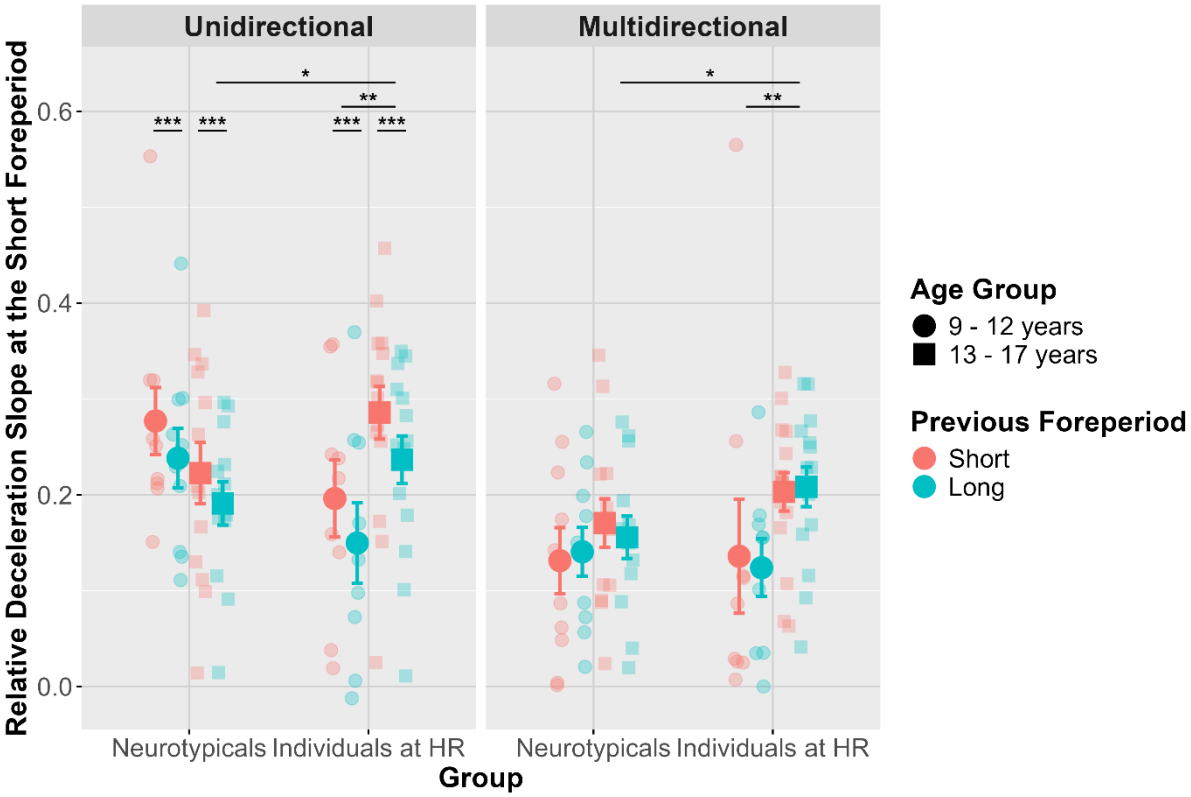

Figure 3. Relative deceleration slopes at the short foreperiod are presented for both motor tasks, across groups and age, depending on the previous foreperiod. Opaque shapes with error bars represent the mean relative deceleration slopes at the short foreperiod ± SEM, while transparent shapes depict individual participants' data points for each condition. In

both panels, the highest significance bar indicates the interaction between the group and age factors, showing a difference between neurotypicals and individuals at HR only in the 13 – 17 age group. The significance bar just below it highlights another difference arising from the interaction between group and age factors, specifically between the 9 – 12 and 13 – 17 age groups among individuals at HR. Finally, the four significance bars in the unidirectional panel illustrate the sequential effect on the relative deceleration slopes across all participants in this task.

3.2.1.2. Long foreperiod (1000 ms – 1700 ms)

In individuals at HR, the skewness of RTs and the variability in the travelled distance during the multidirectional task (see Supplementary Material – Section 2) suggest specific difficulties when motor planning needs to be adjusted. We examined whether this difficulty is related to challenges in adjusting deceleration after the short foreperiod. To capture the adjustment in motor preparation more accurately, we calculated a relative sequential effects index for the long foreperiods (see Methods section 2.5.2.3). This approach helps us understand how participants adapt their motor responses when the target signal does not occur at the short foreperiod. We computed this index by comparing trial sequences with identical foreperiods (long-long sequence) to those with different foreperiods (short-long sequence).

We conducted a three-way mixed ANOVA, with the between-group factors 'group' and ‘age’, and the within-group factor 'task', on the sequential effect index of relative deceleration slopes at the long foreperiod.

The analysis did not reveal any main effects; neither the group factor, age factor, nor task factor influenced the relative deceleration slope before the long foreperiod: [$F(1,43) = 1.98$, $p = .17$, $\eta^2_p = 0.044$], [$F(1,43) = 0.23$, $p = .64$, $\eta^2_p = 0.0050$], and [$F(1,43) = 0.92$, $p = .34$, $\eta^2_p = 0.021$], respectively.

Yet, a significant interaction between ‘group’ and ‘task’ factors was found [$F(1,43) = 11.45$, $p = .0020$, $\eta^2_p = 0.21$]. Independent t-tests with Bonferroni-corrected p-values showed that individuals at HR displayed sequential effects on the relative deceleration slope (0.10 ± 0.23) in the multidirectional task, while neurotypical individuals did not (-

0.04 ± 0.14), t(38.4) = -2.49, p = .035. This indicates that individuals at HR decelerate more at the long foreperiod when the previous foreperiod was also long, compared to when it was short, a pattern not seen in neurotypicals.

We also observed a trend for a three-way interaction [F(1,43) = 3.51, p = .068, η^2_p = 0.080]. The graphical data indicated a difference between neurotypicals and individuals at HR in the 9 – 12 age group during the multidirectional task. To confirm this observation, we conducted independent t-tests with Bonferroni-corrected p-values. These analyses supported the graphical findings, showing a significant difference between individuals at HR (0.14 ± 0.21) and neurotypicals (-0.12 ± 0.16) in the multidirectional task for the 9 – 12 age group, t(14.8) = -3.01, p = .035.

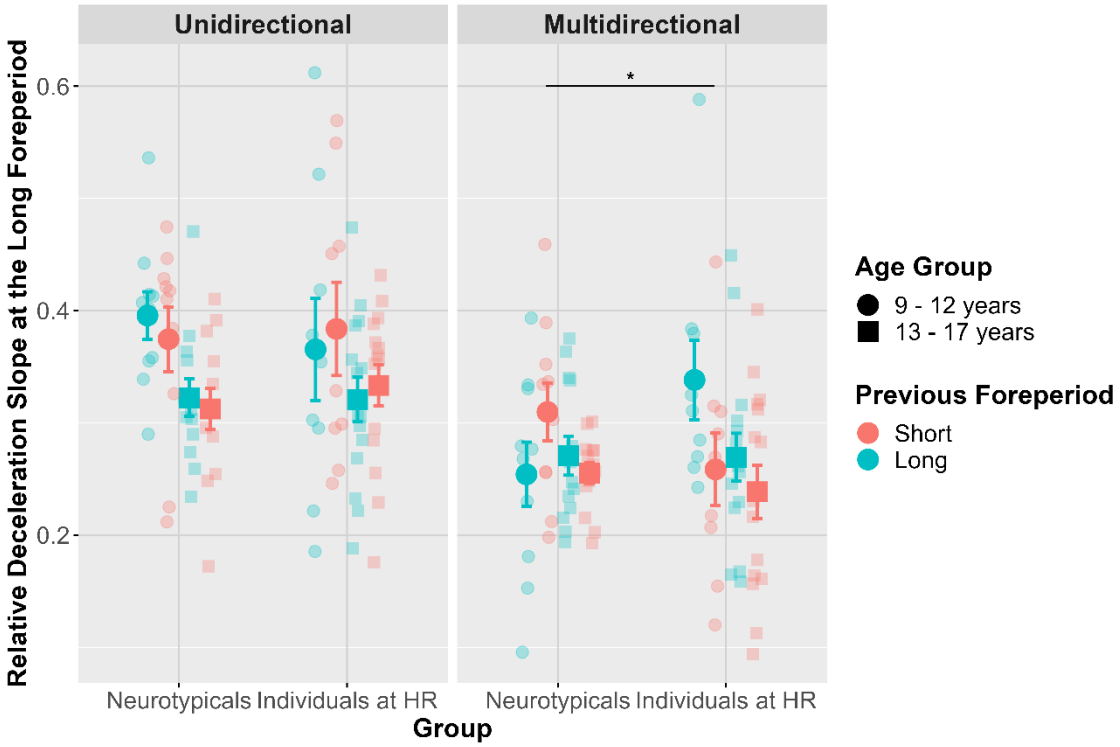

Figure 4. Relative deceleration slopes at the long foreperiod are presented for both motor tasks across groups and ages, depending on the previous foreperiod. Opaque shapes with error bars represent the mean relative deceleration slopes at the long foreperiod ± SEM, while transparent shapes reflect individual participants' data points for each condition. The significant bar in the multidirectional panel highlights the difference between neurotypicals and individuals at HR in the 9 – 12 age group.

4. Discussion

Our results allowed us to replicate the typical variable foreperiod effect as well as the sequential effect usually observed in the variable foreperiod task. These effects were preserved in individuals at HR in the control task, in which participants only reacted to the target signal by pressing a response key. Such results were expected, given the literature showed preserved variable foreperiod and sequential effects at the group level in individuals with SZ (Ciullo et al., 2018; Martin et al., 2017). It is all the more striking that impairments were observed in the tasks including an additional motor component, i.e. the uni- and the multidirectional tasks, in which participants had to perform a motor action while waiting for the sensory target signal (the tactile vibration). Although all the tasks require a motor response, the uni- and multidirectional tasks additionally require to integrate a prediction of the sensory signal within the motor program which is executed while waiting for the target. The expectation of the target signal requires to plan a slowing down of the action in advance of the target, and an adjustment of the action if the target signal does not occur after the short foreperiod. In the typical control task, the motor action can be planned in advance, but is executed only after the occurrence of the target signal. In contrast with the uni- and mutidirectional tasks, the kinematic parameters of the motor action in the control task do not require to be adjusted as a function of the future target signal. The fact that individuals at HR differed from neurotypicals in the motor tasks but not in the control task, suggests that temporal prediction per se is not impaired, but rather the integration of the sensory prediction and its time of occurrence within the motor program. Such results are consistent with the literature suggesting difficult multisensory integration during motor actions (Damme et al., 2021, 2024; Poletti et al., 2017, 2019; Poletti & Raballo, 2022). However, one could argue that the control task is simply less sensitive than the motor tasks, the explaining that a group difference is observed only in the motor tasks. The uni- and multidirectional tasks were designed to more precisely explore whether and how sensory prediction is integrated in the motor program, and additional results helped us to explore sensorimotor integration further.

We replicated the results showing that responses to the target signal (RTs) were influenced by the previous trial when participants always performed the same motor movement from trial to trial (unidirectional task) whereas RTs were less sensitive to previous trials when the direction of the motor movement changed between consecutive trials (multidirectional task) (Arrouet et al., submitted). The motor program is reset when changing direction,

explaining that the temporal characteristics of the previous motor program do not influence the execution of the motor action and the response on the current trial. In other words, the sensory prediction is inherently associated to the motor program only when it is pertinent, i.e. when the motor task does not change. This suggests optimal sensorimotor integration, inasmuch only sensory prediction integrated within the motor program affects subsequent actions, whereas sensory prediction occurring outside the motor program is without effect. Conversely the existence of sequential effects in the multidirectional task suggests suboptimal sensorimotor integration. We already had observed sequential effects in the multidirectional tasks in young neurotypicals (Arrouet et al., in preparation). When the action changes direction, the motor plan has to change, which also implies a change in temporal constraints on the motor program (Miall & Jackson, 2006). For this reason, temporal predictions cannot be derived from the motor plan built for a different action. It is however possible that the time of occurrence of the sensory signal is predicted independently of the motor program. As a matter of fact, we showed before that even when sequential effects disappeared on motor parameters in the multidirectional task, they were still observed on the EEG (Arrouet et al., submitted). Temporal prediction regarding sensory signals is coded independently from the motor program. This means that if there are sequential effects in the multidirectional task, it is likely that these influences originate from outside the motor program. In other words, this suggests that sensory predictions are not being integrated into the motor program, indicating a lack of sensorimotor integration. This is why sequential effects in the multidirectional task are taken as an index of poor sensorimotor integration. In individuals at HR, there is multiple results suggesting poor sensorimotor integration.

The most important results concern sequential effects in the multidirectional task. The sequential effects in the multidirectional task were not absent in the participants of this present study like they were in adults (Arrouet et al., submitted). However, the analysis on the skewness of RTs suggested that individuals at HR were more prone than neurotypicals to show sequential effects, i.e. slowed responses when the current trial was with a short foreperiod and the previous trial with a long foreperiod. The sequential effects on the relative deceleration slope recorded before the shortest possible foreperiod also tended to be larger in individuals at HR than in neurotypicals. During typical development, our previous results had shown sequential effects in the multidirectional task mainly on RTs, but not on deceleration (Arrouet et al., in preparation). The

enlargement and generalization of these effects in individuals at HR was expected. If sensorimotor integration is associated with optimized neurodevelopment, poor sensorimotor integration can be expected when neurodevelopment is affected. Nonetheless it was surprising to see an effect on the kinematic parameters, which should have been reset when the action direction changed. We looked at additional results to better understand what may happen in neurotypicals and individuals at HR and why their motor skills are impaired (Burton et al., 2016; Keskinen et al., 2015).

All young individuals showed slowed responses in the multidirectional task, but young neurotypicals were especially slowed down at short foreperiods. RTs improved for the neurotypicals in the 13 – 17 age group. It might seem surprising that individuals at HR were not slowed down in the multidirectional task. However, the multidirectional task requires to re-plan a motor action on each trial, in addition to integrate the sensory prediction on each trial. This integration is most taxing at short foreperiod, since the probability of target occurrence on this foreperiod is only 50%. The slowing down in young neurotypicals may reflect this uncertainty. As expected, there was no sequential effect on deceleration, indicating that young neurotypicals reset their motor program without integrating the temporal information from the previous trial in the program. As already discussed, in young neurotypicals, sequential effects are observed again at the stage of the response (albeit with a smaller amplitude than for the unidirectional task). Such sequential effects at the stage of the response sign suboptimal sensorimotor integration and may further slowdown responses. This is not what happens in individuals at HR, who integrate the influence of prior trials earlier, already at the stage of deceleration. The action plan is necessarily reset since individuals at HR followed instruction and changed direction. However, sequential effects at the level of deceleration suggests that temporal prediction affecting the kinematic parameters of the action is not integrated in the motor program and originates from an external sensory prediction. This cannot be efficient, and likely implies imprecision in the timing of actions.

One limitation of this reasoning is that the sequential effects in individuals at HR were not clearly increased at the deceleration stage before the short foreperiod. There was only a tendency. However, sequential effects were very clearly abnormal during trials with long foreperiods. This was the most surprising effect in this study, as sequential effects are not usually observed at long foreperiods, because motor responses are supposed to be

optimized at long delays, when the target is bound to occur (Capizzi et al., 2015; Correa et al., 2006; Mento, 2017). This effect is all the more difficult to interpret that it is not an all-or-none effect. Several effects are preserved. Some type of optimization is certainly preserved in individuals at HR, since the usual effect of variable foreperiods was observed in those individuals, i.e. faster responses at long than at short foreperiods. Also, there was no sequential effects at long foreperiods on RTs (stopping latencies). Abnormal sequential effects were selectively observed at the deceleration stage, showing an abnormal influence of the previous trial on motor planning itself. One specificity of the long foreperiod is that the prediction needs to be readjusted after the short foreperiod. It is only when the target has not occurred at the short foreperiod that the continuation of the action can be planned. Research indicates that during neurodevelopment, young neurotypicals tend to rely more on immediate preceding information rather than the overall foreperiod distribution in order to automatically build their predictions (Del Popolo Cristaldi et al., 2023; Mento & Granziol, 2020). It might thus have been possible that individuals are simply less sensitive to the probability of occurrence of the target and more sensitive to the previous trials. Specifically, after the short foreperiod, the probability of occurrence of the target at the long foreperiod is 100%, and the action should be optimal in any case, except if there is an abnormal sensitivity to previous trials. This explanation is unlikely for individuals at HR, however. If this had been the cause of abnormal sequential effects on deceleration, it should also have been observed on RTs. In our study however, the response was optimized and uninfluenced by the previous trial, whether in neurotypicals or in individuals at HR. It is thus unlikely that individuals at HR are unsensitive to the distribution probabilities (Debrabant et al., 2012; Del Popolo Cristaldi et al., 2023; Mento & Granziol, 2020) or impaired at optimizing motor responses (Los et al., 2014, 2017; Salet et al., 2022). The persistence of a sequential effect on deceleration suggests that the planification of the action kinematics is suboptimal. If the temporal prediction used at the motor level is not optimally integrated in the motor program, and is rather influenced by external, sensory influences, it may be possible that the motor program still relies on the temporal properties of previous actions even if those are not pertinent for the present action, and especially at long foreperiods. The need to readjust a motor action may fragilize motor planning even further, thus explaining that abnormal sequential effects on deceleration at long foreperiods are the clearest in individuals at HR.

5. Conclusion

In all the results confirm the literature suggesting a difficulty in sensorimotor integration in individuals at HR (Damme et al., 2021, 2024; Poletti et al., 2017, 2019; Poletti & Raballo, 2022). They allowed us to speculate further about a suboptimal integration of temporal prediction into the motor program in individuals at HR. The results lead to fundamental questions on the integration of time prediction in motor programs. This question has been addressed by proposing the Smith predictor (Miall et al., 1993), which implies that a motor program is planned according to temporal internal constraints (which muscle should be contracted when to achieve an optimal gesture). However, it is not always clear, how external constraints are taken into account. The possible existence of dissociated temporal predictions at the motor and sensory levels (Arrouet et al., submitted) further complicates this question. Its resolution may help to gain even more insights in neurodevelopment and impairments in individuals at HR.

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5.2. Supplementary Material

Section 1 – Control Task

1. Materials and Methods

The purpose of this control task was to confirm the presence of typical effects of temporal prediction abilities observed in standard variable foreperiod tasks found in the literature. This control task was designed to be similar to the motor tasks, featuring the same foreperiods, stimuli, and number of trials; however, participants were instructed to respond only to the target signal by pressing a button, without performing any movements during the foreperiod.

As in the motor task, the trial began with the start signal. After either a short or long foreperiod, the target signal occurred. Participants were instructed to respond as quickly as possible to the onset of the target signal by pressing the central button of a Chronos E-Prime 3.0 response box with their dominant hand.

1.1 Participants

A data recording error resulted in the loss of one participant at HR in the 13 – 17 age group for the control task. Bringing the sample size for this group to 14 participants (compared to 15 in the motor tasks of the main manuscript).

The sample sizes for the other groups remain unchanged in relation to the main manuscript.

1.2 Analyses of Reaction Times

Trials that included omission errors (no response from the participant), incorrect responses (pressing an incorrect button), and anticipated responses (RT < 150 ms) were removed from further analysis.

			Experimental Task
Population group	Age group	Condition	Control
Neurotypicals	9 – 12 years	Short	5
		Long	14
	13 – 17 years	Short	3
		Long	13
Individuals at HR	9 – 12 years	Short	12
		Long	19
	13 – 17 years	Short	6
		Long	11

Table S1.1. Mean number of trials excluded in the behavioural analyses as a function of the population group, age group and condition in the control task (total of trials per condition = 96)

2. Results

2.1 Reaction Times

We investigated the influence of age group on the variable foreperiod effect and sequential effects on RTs in the control task. A four-way mixed ANOVA was conducted on RTs, incorporating the between-group factors of ‘group’ (neurotypicals vs. individuals at HR) and 'age' (9 – 12 years, 13 – 17 years) and the within-group factors of ‘previous foreperiod’ (short vs. long) and ‘current foreperiod’ (short vs. long) (see Figure S1.1).

The analysis revealed a significant main effect of the ‘current foreperiod’ [$F(1,42) = 15.98$, $p = .00025$, $\eta^2_p = 0.28$], consistent with the typical variable foreperiod effect, as indicated by faster RTs for the long current foreperiod (232 ms ± 55) compared to the

short current foreperiod (249 ms ± 66). Additionally, a significant main effect of 'previous foreperiod' was found [$F(1,42) = 41.49$, $p = .000000092$, $\eta^2_p = 0.50$], with faster RTs recorded when the previous foreperiod was short (231 ms ± 58) compared to long (249 ms ± 63). A significant interaction between these two factors was also observed [$F(1,42) = 43.80$, $p = .000000051$, $\eta^2_p = 0.51$]. Paired t-tests confirmed the asymmetrical sequential effects on RTs, showing slower RTs during the short foreperiod only when preceded by a long foreperiod (266 ms ± 64) compared to a short foreperiod (231 ms ± 64), $t(45) = -8.14$, $p = .00000000021$. There was no impact of the previous foreperiod when the current one was long, $t(45) = -0.18$, $p = .89$.

There was a significant main effect of the 'age' factor [$F(1,42) = 7.86$, $p = .0080$, $\eta^2_p = 0.16$], with faster RTs in the 13 – 17 age group (222 ms ± 38) compared to the 9 – 12 age group (266 ms ± 77). However, no significant main effect was observed for the 'group' factor [$F(1,42) = 1.06$, $p = .31$, $\eta^2_p = 0.025$], and no other significant interactions were found (all ps > .05).

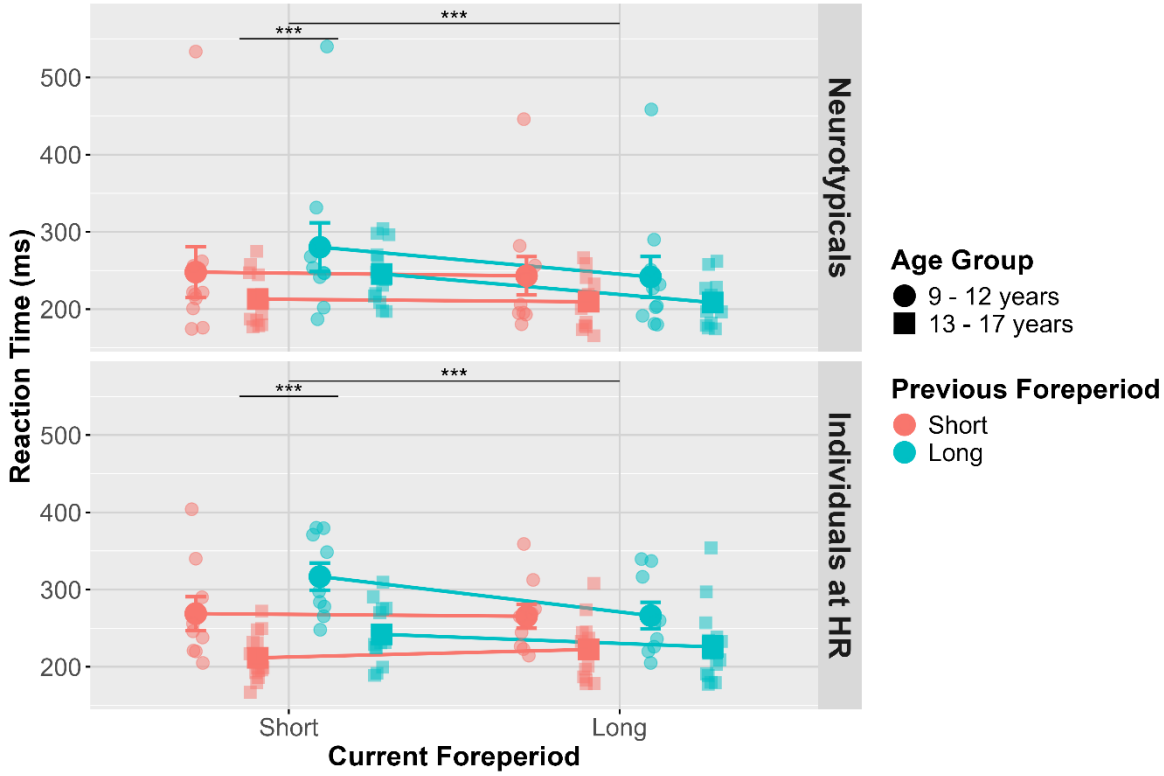

Figure S1.1. RTs in ms at the current foreperiod in the control task, categorized by population group (one per panel), age group, and the previous foreperiod. Opaque shapes with error bars represent the mean RT ± standard error of the mean (SEM), while

transparent shapes illustrate individual data points for each participant in the respective conditions. Statistical significance is indicated by *** for p-values < .001. In both panels, the upper significance bar denotes the main effect of the current foreperiod factor, while the leftmost bar in the graph indicates the sequential effect, highlighting that the previous foreperiod affects RT only when the current foreperiod is short.

3. Conclusion

Neurotypicals and individuals at HR showed classical temporal prediction abilities, including intact variable foreperiod and sequential effects in the control task. There was no difference in RT speed between the two groups, indicating similar performance. The effect of the age factor on RTs aligns with existing literature, showing that older individuals have faster RTs than younger ones (Adams & Lambos, 1986; Johnson et al., 2015).

Section 2 – Motor Tasks

1. Materials and Methods

1.1 Stopping point

1.1.1 Stopping point criteria in the multidirectional task

To define a stopping point, the first criterion required that speed decrease by at least 40% from the previous maximum speed. For example, if the maximum speed was 10 cm/sec, the speed at the stopping point needed to be 6 cm/sec or lower. While this criterion indicated a significant reduction in speed, it did not guarantee a complete stop since participants could still decelerate without halting. To address this, a second criterion was added: a stopping point was confirmed only if the next two speed peaks were below twice the speed at the stopping point. In the previous example, if the stopping speed was 6 cm/sec, the subsequent peaks had to be below 12 cm/sec.

These two criteria alone were not sufficient to confirm a complete stop because the participant's finger might tremble, preventing the speed from reaching zero. Instead of using zero as the threshold, we established a stopping threshold based on the speed due to tremors. We calculated the median speed peak for each trial (between 0 and 3000 ms), as it effectively represented tremor speed. Tremor-related peaks were often irregular, making the median peak a reliable indicator (see Figure 1 in the main manuscript). The third criterion required that the speed at the stopping point must not exceed 1.5 times the median speed peak for that trial. For instance, if the stopping speed was 6 cm/sec, the median peak had to be 9 cm/sec or lower. The combination of these three rules allowed accurate identification of stopping points, which we confirmed through visual checks.

1.1.2 Stopping point criteria in the unidirectional task

The criteria for the unidirectional task were adjusted due to participants returning to the starting point after stopping, making the stopping less obvious and the stationary period shorter. Therefore, we modified the criteria: at the stopping point, speed needed to decrease by at least 30% from the previous maximum speed (compared to 40% in the multidirectional task). The second criterion remained the same: the stopping point was accepted only if the next two speed peaks were less than double the stopping point speed.

If the standstill period was too brief, subsequent peaks might not be below twice the stopping point speed since participants often returned quickly to the starting point, resulting in the next peak being the highest of the trial. In such cases, the stopping point was accepted if the speed of the next peak was at least 50% of the maximum speed for that trial. Finally, to ensure a complete stop, we added a criterion: the speed at the stopping point must be no more than 35% of the maximum speed when returning to the starting position. Visual checks confirmed that this 35% threshold was appropriate, as a lower percentage would have missed some true stopping points.

1.2 First deceleration point (150 – 1000 ms) criteria

For the first deceleration point, we established a time window of 150 to 1000 ms. A minimum of 150 ms is necessary for the brain to process the start signal and send a motor command (Jana et al., 2020). Any deceleration point occurring before 150 ms was

classified as an anticipation. If the target signal was expected at 1000 ms, participants should start slowing down before this time. As with the stopping point criteria, we confirmed these criteria through visual checks for each trial and participant.

The first criterion stated that the speed at the first deceleration point must be at least 30% of the maximum speed within the designated time window. Visual assessments indicated that this 30% threshold effectively balanced avoiding omission and false alarms. Two additional criteria ensured that participants were effectively decelerating and not preparing to accelerate again. The speed at the next peak had to be at least 10% slower than the speed at the first deceleration point, or the acceleration at the next peak had to be 30% lower than the acceleration at the first deceleration point.

1.3 Second deceleration point (1000 – 1700 ms) criteria

In trials with a long foreperiod, if the target signal did not appear by 1000 ms, participants had to continue moving until 1700 ms, which may have led to updates in their predictions. The criteria for identifying the second deceleration point were the same as those for the first deceleration point, with the only difference being the relevant time window, which extended from 1000 ms to 1700 ms.

2. Results

2.1 Reaction times statistics

Effect	DF	F	p-value	η^2_p
Group	(1,43)	0.044	.84	0.0010
Age	(1,43)	12.00	.0010	0.22
Task	(1,43)	96.97	.0000000000014	0.69
Previous FP	(1,43)	28.14	.0000037	0.40
Current FP	(1,43)	196.26	.000000000000000013	0.82
Group * Age	(1,43)	0.27	.61	0.0060
Group * Task	(1,43)	1.21	.28	0.027
Age * Task	(1,43)	6.92	.012	0.14

Group * Previous FP	(1,43)	0.40	.53	0.0090
Age * Previous FP	(1,43)	1.45	.23	0.033
Group * Current FP	(1,43)	0.10	.75	0.0020
Age * Current FP	(1,43)	6.31	.016	0.13
Task * Previous FP	(1,43)	10.11	.0030	0.19
Task * Current FP	(1,43)	3.39	.0073	0.073
Previous FP * Current FP	(1,43)	36.91	.00000028	0.46
Group * Age * Task	(1,43)	1.30	.26	0.029
Group * Age * Previous FP	(1,43)	0.07	.81	0.0010
Group * Age * Current FP	(1,43)	0.53	.47	0.012
Group * Tache * Previous FP	(1,43)	3.88	.056	0.083
Age * Tache * Previous FP	(1,43)	0.078	.78	0.0020
Group * Tache * Current FP	(1,43)	1.58	.22	0.035
Age * Tache * Current FP	(1,43)	1.88	.18	0.042
Group * Previous FP * Current FP	(1,43)	1.18	.28	0.027
Age * Previous FP * Current FP	(1,43)	2.64	.11	0.058
Tache * Previous FP * Current FP	(1,43)	3.39	.073	0.073
Group * Age * Task * Previous FP	(1,43)	0.29	.60	0.0070
Group * Age * Task * Current FP	(1,43)	4.11	.050	0.087
Group * Age * Previous FP * Current FP	(1,43)	0.56	.46	0.013
Group * Task * Previous FP * Current FP	(1,43)	0.29	.60	0.0070
Age * Task * Previous FP * Current FP	(1,43)	0.37	.55	0.0080
Group * Age * Task * Previous FP * Current FP	(1,43)	0.14	.71	0.0030

Table S2.1. Comprehensive statistical results of the five-way mixed ANOVA on RTs, including the following between-group factors: 'group' (neurotypicals vs. individuals at HR) and 'age' (9 – 12 years vs. 13 – 17 years), and the within-group factors: 'previous foreperiod' (short vs. long), 'current foreperiod' (short vs. long), and 'task' (unidirectional vs. multidirectional). For abbreviation, FP = foreperiod.

Effect	DF	F	p-value	η^2_p
Age	(1, 21)	9.63	.0050	0.31
Previous FP	(1, 21)	12.89	.0020	0.38
Current FP	(1, 21)	59.68	.00000014	0.74
Age * Previous FP	(1, 21)	0.054	.82	0.0030
Age * Current FP	(1, 21)	7.80	.011	0.27
Previous FP * Current FP	(1, 21)	12.73	.0020	0.38
Age * Previous FP * Current FP	(1,21)	2.30	.14	0.010

Table S2.2. This sub-analysis presents the comprehensive statistical results of the three-way mixed ANOVA on RTs of the neurotypical group during the multidirectional task. It includes the between-group factor 'age' (9–12 years vs. 13–17 years) and the within-group factors 'previous foreperiod' (short vs. long) and 'current foreperiod' (short vs. long). Abbreviation: FP = foreperiod.

2.2 Skewness statistics

Effect	DF	F	p-value	η^2_p
Group	(1,43)	0.94	.34	0.021
Age	(1,43)	8.59	.0050	0.17
Task	(1,43)	23.11	.000019	0.35
Previous FP	(1,43)	0.021	.89	0.00049
Group * Age	(1,43)	1.94	.17	0.043
Group * Task	(1,43)	10.43	.0020	0.20
Age * Task	(1,43)	0.63	.43	0.014
Group * Previous FP	(1,43)	4.70	.036	0.10
Age * Previous FP	(1,43)	0.72	.40	0.016

Task * Previous FP	(1,43)	0.030	.86	0.00070
Group * Age * Task	(1,43)	0.53	.47	0.012
Group * Age * Previous FP	(1,43)	0.030	.86	0.00070
Group * Tache * Previous FP	(1,43)	0.0090	.93	0.00021
Age * Tache * Previous FP	(1,43)	0.53	.47	0.012
Group * Age * Task * Previous FP	(1,43)	0.79	.38	0.018

Table S2.3. Comprehensive statistical results of the four-way mixed ANOVA on response skewness, incorporating the following between-group factors: 'group' (neurotypicals vs. individuals at HR) and 'age' (9 – 12 years vs. 13 – 17 years), and the within-group factors: 'previous foreperiod' (short vs. long) and 'task' (unidirectional vs. multidirectional). For abbreviation, FP = foreperiod.

2.3 Relative deceleration slopes at the short foreperiod

2.3.1 Raw data

Effect	DF	F	p-value	η^2_p
Group	(1,43)	0.0050	. 94	0.00013
Age	(1,43)	2.65	.11	0.058
Task	(1,43)	14.17	.00050	0.25
Previous FP	(1,43)	6.38	.015	0.13
Group * Age	(1,43)	4.74	.035	0.099
Group * Task	(1,43)	0.91	.35	0.021
Age * Task	(1,43)	0.87	.36	0.020
Group * Previous FP	(1,43)	0.14	.71	0.0030
Age * Previous FP	(1,43)	0.0010	.97	0.000030
Task * Previous FP	(1,43)	6.01	.018	0.12
Group * Age * Task	(1,43)	1.66	.20	0.37
Group * Age * Previous FP	(1,43)	0.20	.66	0.0050
Group * Tache * Previous FP	(1,43)	0.15	.70	0.0030

Age * Tache * Previous FP	(1,43)	0.032	.86	0.00075
Group * Age * Task * Previous FP	(1,43)	0.67	.42	0.015

Table S2.4. Comprehensive statistical results of the four-way mixed ANOVA on relative deceleration slopes at the short foreperiod, incorporating the following between-group factors: 'group' (neurotypicals vs. individuals at HR) and 'age' (9 – 12 years vs. 13 – 17 years) and the within-group factors: 'previous foreperiod' (short vs. long) and 'task' (unidirectional vs. multidirectional). For abbreviation, FP = foreperiod.

To investigate the significant interaction between the 'age' and 'group' factors, we conducted independent t-tests with Bonferroni-corrected p-values. The results indicated that individuals at HR had steeper slopes (0.23 ± 0.10) compared to neurotypicals (0.19 ± 0.09) only in the 13 – 17 years age group, $t(108.1) = -2.74$, $p = .029$. Furthermore, among individuals at HR, the 13 – 17 years age group exhibited steeper slopes than the 9 – 12 years age group (0.15 ± 0.13), $t(57.7) = -3.33$, $p = .0060$.

2.3.2 Sequential effect index

Effect	DF	F	p-value	η^2_p
Group	(1,43)	3.26	.078	0.070
Age	(1,43)	0.024	.88	0.00055
Task	(1,43)	7.87	.008	0.16
Group * Age	(1,43)	3.11	.085	0.067
Group * Task	(1,43)	0.88	.36	0.020
Age * Task	(1,43)	3.65	.063	0.078
Group * Age * Task	(1,43)	0.0060	.94	0.00014

Table S2.5. Comprehensive statistical results of the three-way mixed ANOVA on the sequential effect on relative deceleration slopes, incorporating the following between-group factors: 'group' (neurotypicals vs. individuals at HR) and 'age' (9 – 12 years vs. 13 – 17 years) and the within-group factor 'task' (unidirectional vs. multidirectional).

2.4 Variability of the travelled distance

By examining the variability of the travelled distance, we assessed the consistency of trajectories and whether stable motor preparation was maintained across trials. Given that trajectory variability may relate to movement length, we accounted for current foreperiods, as longer foreperiods typically result in longer movements. We also included the previous foreperiod to evaluate how reusing (or not) the same motor program might affect trajectory stability in each group.

We conducted a five-way mixed ANOVA on the variability of the travelled distance, with the between-group factors 'group' (neurotypicals vs. individuals at HR) and ‘age’ (9 – 12 years vs.13 – 17 years) and within-group factors 'task' (unidirectional vs. multidirectional), 'previous foreperiod' (short vs. long), and 'current foreperiod' (short vs. long) (Figure S2.1).

The analysis revealed a significant main effect of the 'age' factor [$F(1,43) = 11.59$, $p = .001$, $\eta^2_p = 0.21$], indicating greater variability in the travelled distance in the 9 – 12 years group (4.80 cm ± 3.3) compared to the 13 – 17 years group (2.98 cm ± 1.8). A main effect of the 'task' factor was also observed [$F(1,43) = 5.33$, $p = .026$, $\eta^2_p = 0.11$], with all participants showing greater variability in the multidirectional task (4.12 cm ± 2.5) than in the unidirectional task (3.30 cm ± 2.8). Additionally, a significant effect of 'current foreperiod' was found [$F(1,43) = 80.61$, $p = .000000000021$, $\eta^2_p = 0.65$], demonstrating increased variability in the travelled distance at the long foreperiod (4.31 cm ± 2.8) compared to the short foreperiod (3.11 cm ± 2.4). We found no main effect of the ‘group’ [$F(1,43) = 0.005$, $p = .94$, $\eta^2p = 0.0001$] nor the ‘previous foreperiod’ [$F(1,43) = 0.005$, $p = .94$, $\eta^2_p = 0.0001$] factors.

A significant interaction between 'task' and 'current foreperiod' was observed [$F(1,43) = 13.40$, $p = .00069$, $\eta^2_p = 0.24$]. Paired t-tests indicated that variability in travelled distance was higher at the long foreperiod (4.95 cm ± 2.6) compared to the short foreperiod (3.29 cm ± 2.0) specifically in the multidirectional task, $t(93) = -4.12$, $p < .001$.

Finally, an interaction between 'group' and 'task' factors was identified [$F(1,39) = 5.14$, $p = .03$, $\eta^2_p = 0.12$]. Independent t-tests with Bonferroni corrections showed a trend towards

greater variability of the travelled distance in individuals at HR during the multidirectional task (4.65 cm ± 2.7) compared to the unidirectional task (3.03 cm ± 1.4), $t(184.3) = -2.13$, $p = .068$. This pattern was not observed in neurotypicals, $t(115.9) = 1.78$, $p = .16$. These findings suggest that for individuals at HR, using a different motor program at each trial affects the consistency of their motor execution. No other interactions were significant (all ps > .05).

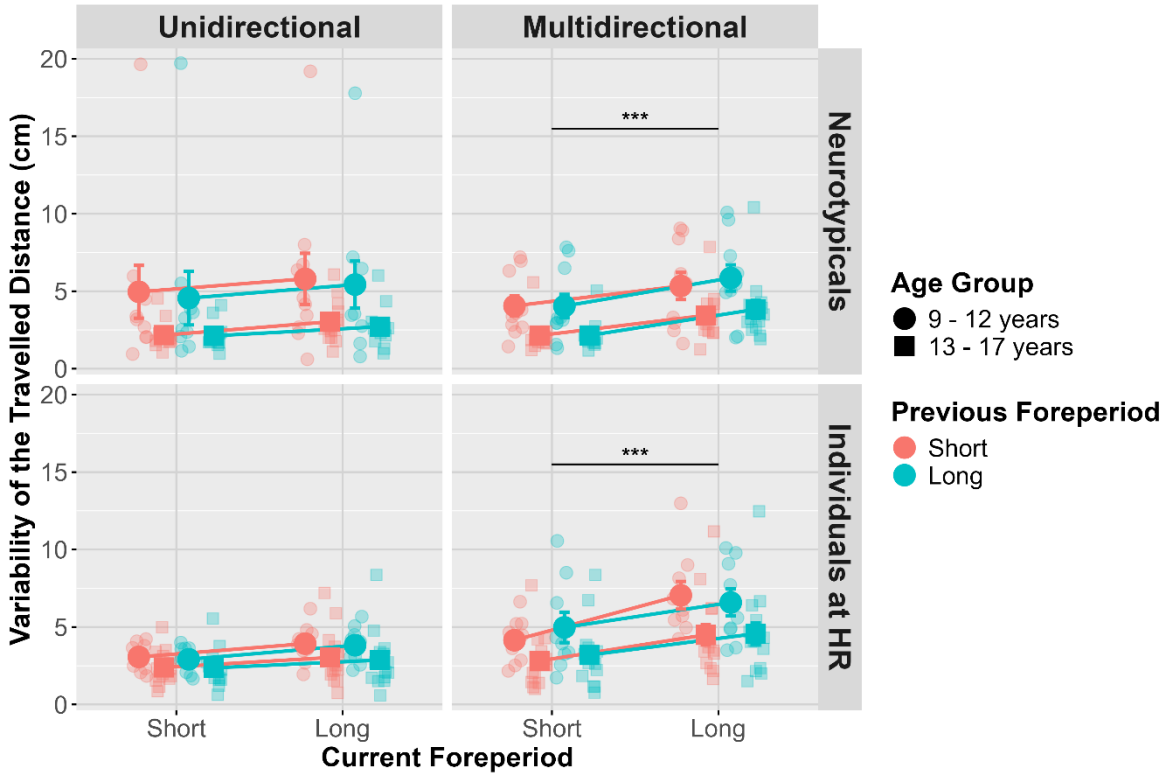

Figure S2.1. Variability in the traveled distance (in cm) at the current foreperiod for both motor tasks, categorized by group, age, and previous foreperiod. Opaque shapes with error bars indicate the mean traveled distance ± SEM, while transparent shapes represent individual participants' data points for each condition. Statistical significance is denoted by *** for p-values < .001 and ** for p-values < .01. In the multidirectional task, the significant bars indicate the interaction effect between the task and current foreperiod, showing greater variability in traveled distance for short trials compared to long trials in both neurotypicals and individuals at HR.

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Rappel des résultats principaux de l'étude 3

L'étude 3 visait à observer la manière dont la prédiction temporelle associée à l'occurrence d'un signal sensoriel influence le comportement moteur d'une population d'individus à HR de conversion psychotique. Pour ce faire, nous avons employé nos deux tâches motrices, à savoir la multidirectionnelle et l'unidirectionnelle, sur des participants âgés de 9 à 17 ans. L'objectif était de vérifier la présence d'effets séquentiels sur des indicateurs associés à la préparation (ralentissement anticipatoire) et à l'exécution (temps de réaction, TR) de l'arrêt.

Les neurotypiques et les individus à HR ont montré des effets séquentiels sur leurs TRs dans les deux tâches motrices. Comme indiqué dans l'étude 2, ces effets reflètent une prédiction temporelle liée à l'occurrence du signal cible qui ne s'intègre pas à une commande motrice précise, ce qui explique leur persistance malgré le changement de direction entre les essais. Ainsi, la présence d'effets séquentiels dans cette tâche est considérée comme un signe d'une intégration sensorimotrice immature. L'analyse de la distribution des TRs a révélé que les individus à HR étaient plus sensibles aux effets séquentiels dans la tâche multidirectionnelle que les participants neurotypiques. En particulier, au délai court, leurs TRs montrent une distribution asymétrique, avec des réponses plus lentes lorsque le délai précédent était long plutôt que court. Ce résultat suggère une intégration sensorimotrice encore moins mature chez le groupe d'individus à HR comparativement aux neurotypiques.

Concernant les ralentissements anticipatoires de l'arrêt, nous avons observé des effets séquentiels chez les individus à HR dans les tâches unidirectionnelle et multidirectionnelle. Dans la tâche multidirectionnelle, ces effets n'étaient qu'une tendance au délai court, mais se sont révélés significatifs au délai long. Normalement, des effets séquentiels ne devraient pas apparaître dans cette tâche, car la commande motrice change d'un essai à l'autre. La persistance de ces effets pourrait indiquer un déficit dans l'intégration de la prédiction temporelle motrice lors de la planification du mouvement. Ainsi, la planification pourrait être davantage influencée par une prédiction sensorielle externe, qui ne s'intègre pas correctement à la commande motrice chez les individus à

HR. Nous avons proposé que la présence d'effets séquentiels au délai long suggère que la prédiction temporelle concernant l'occurrence du signal cible n'est pas prise en compte lors de la décélération. Dans la tâche multidirectionnelle, la nécessité de réajuster une action motrice pourrait fragiliser davantage la planification, ce qui explique pourquoi des effets séquentiels anormaux sur la décélération sont plus marqués au délai long qu'au délai court chez les individus à HR.

Objectif de l'étude 4

L'objectif initial de cette étude était de déterminer si l'ajout d'une composante motrice et de stimuli tactiles à un protocole d'attente temporelle pourrait sensibiliser la détection des altérations de la prédiction temporelle chez les individus atteints de SZ chronique. En effet, les troubles de la prédiction temporelle sont liés aux altérations du sens de soi dans la SZ, et l'intégration de la motricité et de la modalité tactile s'avère particulièrement pertinente dans ce contexte.

Les résultats obtenus dans nos trois précédentes études nous amènent à enrichir l'objectif de cette étude 4, qui permettra aussi de vérifier si les prédictions temporelles associées à la planification (prédiction temporelle motrice) et à l'exécution (prédiction temporelle sensorimotrice) d'une action motrice sont altérées dans la SZ.

Cette étude est toujours en cours et les résultats présentés sont préliminaires.

CHAPITRE 6. ÉTUDE PRÉLIMINAIRE CHEZ L'INDIVIDU ATTEINT DE SCHIZOPHRÉNIE

6.1. Manuscrit Principal

1. Introduction

Depuis plus d'un siècle, phénoménologues et psychiatres ont établi un lien entre les troubles de la perception du temps, observés chez les personnes atteintes de schizophrénie (SZ), et les perturbations du sens de soi également rapportées par ces individus (Fuchs, 2007; Martin et al., 2017, 2018; Minkowski, 2013; Parnas & Handest, 2003). Chez les neurotypiques, le passage du temps est expérimenté comme un flux continu, et les événements discontinus qui se succèdent sont pris dans ce flux. Cette continuité temporelle permet de se sentir immergé dans son environnement et participe à donner un sentiment de cohérence de soi. Certains individus atteints de SZ rapportent ne pas percevoir le temps comme le flux continu qu'il devrait être, mais plutôt comme 'de petits morceaux, secoués et mêlés' (traduit de Spitzer, 1988). Pour ces individus, avoir une image de soi unifiée et cohérente à travers le temps s'avère difficile : comment parvenir à une perception continue de soi si le temps lui-même n'est pas continu ?

Des approches expérimentales ont tenté d'objectiver les troubles du soi et du temps, rapportés par les individus atteints de SZ. Par exemple, il est possible de tester en laboratoire les limites corporelles des participants, et par extension, leur soi corporel, avec l'illusion de la main en caoutchouc (Botvinick & Cohen, 1998). Dans cette illusion, la main réelle des participants est cachée de leur vue, tandis qu'une main en caoutchouc est placée devant eux. Les expérimentateurs stimulent simultanément la main cachée et la main en caoutchouc à l'aide de pinceaux. Après un certain temps de stimulation synchrone, les participants commencent à ressentir le toucher sur la main en caoutchouc comme s'il s'agissait de leur propre main. Ces effets surviennent grâce à la synchronisation des stimulations visuelles et tactiles. Cette intégration multisensorielle trompe les frontières corporelles. Les stimulations tactiles perçues sur la main cachée sont associées à la vision de ces stimulations sur la main en caoutchouc, ce qui conduit le participant à percevoir cette main comme la sienne. Chez les individus atteints de SZ,

cette illusion se manifeste plus rapidement et avec plus d'intensité que chez les neurotypiques. Ces résultats suggèrent que les frontières corporelles des personnes atteintes de SZ sont plus floues que celles des neurotypiques (Harduf et al., 2023; Sandsten et al., 2020; Thakkar et al., 2011).

Des données expérimentales ont montré que la simple anticipation d'une stimulation tactile pouvait suffire à induire l'illusion de la main en caoutchouc. Lorsque le mouvement du pinceau est interrompu avant de toucher la main en caoutchouc, c'est-à-dire quand la stimulation tactile n'est pas perçue et ne peut être qu'anticipée, prédite, l'illusion se manifeste tout de même (Ferri et al., 2017). Les résultats montrent que cette procédure permet d'activer les cortex pariétaux multisensoriels de la même manière que la perception d'une stimulation tactile réelle. De plus, cette activité cérébrale est corrélée à la force de l'illusion (Ferri et al., 2013). Ces résultats suggèrent que le sens du soi corporel ne se construit pas seulement à partir de l'intégration multisensorielle, mais également par l'anticipation des signaux somesthésiques. Lorsque l'illusion repose sur l'anticipation plutôt que sur la perception réelle des stimuli, elle est plus marquée chez les neurotypiques que chez les individus atteints de SZ (Ferri et al., 2014). Cette observation suggère que les individus atteints de SZ n'anticipent pas les stimuli tactiles de la même manière que les neurotypiques, et que des altérations des mécanismes prédictifs pourraient contribuer aux troubles du soi corporel observés chez ces individus.

Les recherches de Graham et al. (2014) ont souligné le lien entre les altérations des mécanismes de l'illusion de la main en caoutchouc et de la perception temporelle. Ces recherches font écho aux observations cliniques soulignées plus haut. D'autres données expérimentales ont souligné le lien entre altération des capacités de prédiction temporelle et du sens de soi dans la SZ (Foerster & Joos et al., 2024; Martin et al., 2017). Les capacités de prédiction temporelle peuvent être mesurées grâce à des tâches d'attente temporelle. Dans ce type de tâche, un premier stimulus indique le début de l'essai, suivi, après un délai court ou long, par une cible. Il est bien établi dans la littérature que plus la cible est présentée tardivement, plus la réaction du participant sera rapide, ce qui se traduit par un temps de réaction (TR) plus court (Coull, 2009; Niemi & Näätänen, 1981; Woodrow, 1914). Ce phénomène est expliqué par l'évolution des probabilités d'occurrence de la cible : au fur et à mesure que le temps passe, la probabilité d'apparition de la cible et le niveau de préparation augmentent conjointement. Dans ce type de

protocole, le passage du temps est utilisé de manière implicite ; les participants n'améliorent pas consciemment leur performance en se basant sur le passage du temps, cela se fait automatiquement (Los et al., 2017; Nobre et al., 2007; pour une autre interprétation voir Salet et al., 2022; Vangkilde et al., 2012).

Dans les tâches d'attente temporelle, le bénéfice lié au passage du temps semble être préservé chez certains individus atteints de SZ (Ciullo et al., 2018). Cependant, Martin et al., (2017) ont montré que ce n'est pas le cas pour tous : chez les individus présentant des troubles du sens de soi, les TRs ne diminuent pas avec le passage du temps. Des résultats récents ont permis de mieux quantifier ce phénomène, confirmant au niveau du groupe que tous les individus atteints de SZ présentent une altération de ce bénéfice du passage du temps sur leurs performances (Foerster & Joos et al., 2024). Comme dans l'étude de Martin et al., (2017) cette altération est corrélée aux troubles du sens de soi.

Foerster et Joos et al. (2024) ont observé une altération du bénéfice du passage du temps chez les individus atteints de SZ, même lorsque ceux-ci pouvaient préparer leur réponse motrice avant l'apparition de la cible. la préparation motrice n'était pas possible dans l'étude initiale de Martin et al., (2017), où les participants devaient répondre en fonction du côté d'apparition de la cible (droite ou gauche). Ces résultats indiquent que, même lorsque la réponse motrice peut être préparée en amont, les individus atteints de SZ ne bénéficient pas du passage du temps pour améliorer leurs TRs, contrairement aux neurotypiques. Toutefois, le TR est un indicateur mesuré après l’exécution du mouvement et ne permet pas de capturer la mise en place de la préparation motrice pendant l’attente. Dans notre étude 1 (chapitre 3, page 30), nous avons montré que chez les neurotypiques, exécuter un mouvement pendant l'attente d'un stimulus prédictible implique une prédiction temporelle intrinsèquement liée au mouvement réalisé. Cette observation soulève des questions sur l'état de cette prédiction temporelle chez les individus atteints de SZ. La présente étude explore comment l'exécution d'un mouvement pendant l’attente influence la capacité des individus atteints de SZ à anticiper l'occurrence d'un stimulus prédictible, en mesurant à la fois la réponse comportementale et la réponse électroencéphalographique (EEG).

Dans les tâches d’attente temporelle, les informations des essais précédents peuvent être automatiquement utilisées pour ajuster la préparation à l'essai actuel, ce sont les effets

séquentiels. Quelle que soit la théorie proposée pour expliquer les effets séquentiels, selon ces effets, les participants s'attendent automatiquement à ce que deux essais consécutifs soient similaires. Par exemple, si la cible survient au délai court, il est automatiquement prédit qu'à l'essai suivant la cible survient également au délai court (séquence court-court). Si tel est le cas, la préparation est optimale, ce qui se traduit par des TRs rapides. Si la cible survient au délai long, et qu'à l'essai suivant, elle survient au délai court (séquence long-court), elle arrive plus tôt que prévu. Ceci induit un effet de surprise et ralentit leur TR par rapport à la séquence court-court. Ces effets séquentiels sont dits asymétriques puisqu'au délai long, peu importe le délai précédent, les performances sont toujours optimales. Il a été montré dans la littérature que ces effets séquentiels sont indépendants de la capacité à bénéficier du passage du temps et influencent à la fois les mesures comportementales et EEG (Correa et al., 2006; Los & Heslenfeld, 2005; Mento, 2017; Vallesi et al., 2014; Vallesi & Shallice, 2007; Van der Lubbe et al., 2004; Woodrow, 1914).

La manière dont les effets séquentiels influencent les performances des participants semble similaire entre individus atteints de SZ et neurotypiques (Ciullo et al., 2018; Martin et al., 2017). Toutefois, une sensibilité excessive aux informations issues des essais précédents a été observée chez les individus atteints de SZ dans le domaine moteur (Foerster et al., 2021). Dans cette étude, les participants devaient réaliser une tâche de pointage à l'aide d'un stylet connecté à un dispositif haptique, conçu pour simuler le retour tactile d'un contact avec une surface. A certains essais et de manière imprévisible, le retour haptique était retardé. Même lorsque ces retards étaient imperceptibles, les individus atteints de SZ adaptaient leur trajectoire en fonction du retard de l'essai précédent. La planification d'un mouvement implique une prédiction du retour sensoriel attendu (McNamee & Wolpert, 2019), lequel contribue au sentiment de contrôle des participants sur leur action (Weibel et al., 2015). Lorsque le retour sensoriel est légèrement retardé par rapport à la prévision, cette petite erreur de prédiction est généralement ignorée. C'est ce qui est observé chez les neurotypiques, qui, malgré ce retard, n'ajustent pas leur planification motrice et continuent de décélérer de manière similaire à chaque essai. A l'inverse les individus atteints de SZ ne semblent pas pouvoir ignorer un retard infime du retour sensoriel.

D’autres études ont montré que les individus atteints de SZ sont anormalement sensibles à des délais très courts. Par exemple le signal EEG enregistré en réponse à des signaux visuels légèrement asynchrones (décalés de 24 ms) est d’amplitude plus importante chez les individus atteints de SZ que les neurotypiques (Marques-Carneiro et al., 2021). Ces résultats ont conduit à l'hypothèse que, dans la SZ, la continuité du passage du temps pourrait être rompue par des perturbations à l’échelle de la milliseconde (Giersch & Mishara, 2017). Nous avons voulu savoir si l’attente temporelle était toujours perturbée dans des tâches avec une composante motrice, qui nous permettent d’évaluer la prédiction via les propriétés cinématiques du mouvement pendant l’attente.

Les tâches utilisées dans ce travail reposent sur l’exécution motrice, laquelle pourrait être altérée chez les individus atteints de SZ (Peralta et al., 2010; Walther & Strik, 2012). Cependant, selon les résultats du laboratoire, ces altérations pourraient davantage concerner des mouvements qui nécessitent une séquence d’action plutôt que des mouvements simples (Delevoye-Turrell et al., 2007). Lorsque les individus atteints de SZ réalisent un mouvement en une seule étape, sans devoir le décomposer en plusieurs éléments, leurs performances sont équivalentes à celles des neurotypiques.

Dans cette étude, nous explorons comment l'exécution d'un mouvement simple et continu pendant l'attente d'un stimulus prédictible influence la capacité des individus atteints de SZ à y réagir. Nous avons demandé aux participants d'effectuer un mouvement en ligne droite, ce qui devrait donc limiter les altérations liées au contrôle moteur. Plus précisément, les participants devaient initier un mouvement après un signal de départ et l’arrêter aussi rapidement que possible après l’occurrence d’un signal cible.

Nous avons utilisé deux tâches motrices : une tâche unidirectionnelle, où les participants se déplacent toujours dans la même direction, et une tâche multidirectionnelle, où ils changent de direction à chaque essai. Dans la tâche unidirectionnelle, nous avons observé des effets séquentiels sur les latences d’arrêt (ou TR). Au délai court, les TRs sont plus rapides lorsque le signal cible était également survenu au délai court lors de l'essai précédent, plutôt qu'au délai long (Arrouet et al., soumis). Cet effet séquentiel n’est pas observé dans la tâche multidirectionnelle, mais il l’est dans la tâche unidirectionnelle. Dans la tâche unidirectionnelle la répétition du mouvement dans la même direction, permet de maintenir le programme moteur d’essai en essai, alors qu’il doit être réinitialisé

dans la tâche multidirectionnelle. L'existence des effets séquentiels dans la tâche unidirectionnelle uniquement suggère que la prédiction temporelle est étroitement associée au programme moteur.

Si l'exécution de mouvements simples est préservée chez les individus atteints de SZ, on peut s'attendre à ce que cette prédiction temporelle liée à l'action motrice le soit également. Dans ce cas, nous faisons l'hypothèse d'observer des performances équivalentes entre les individus atteints de SZ et les neurotypiques.

Dans notre tâche, nous recueillons également les réponses EEG des participants, en nous intéressant particulièrement à la variation contingente négative (CNV). Cette onde cérébrale est associée aux capacités de prédiction temporelle, puisqu'elle apparaît après le premier stimulus et persiste jusqu'au stimulus cible (Breska & Deouell, 2014; Pfeuty et al., 2005; Walter et al., 1964). Nos travaux précédents chez les individus neurotypiques ont montré que les effets séquentiels sur l'amplitude de la CNV persistaient dans la tâche multidirectionnelle. Ceci est cohérent avec la littérature et indique que ces effets reflètent un type de prédiction temporelle indépendant du geste effectué (Arrouet et al., soumis; Capizzi et al., 2013; Mento, 2017; Mento et al., 2013; Van der Lubbe et al., 2004). Des études antérieures ont montré que les individus atteints de SZ ont une amplitude de CNV réduite par rapport aux individus neurotypiques (Osborne et al., 2020) et qu'ils ne bénéficient pas des informations issues des essais précédents pour moduler l'amplitude de leur CNV (Ford et al., 2010). Dans nos tâches, la CNV reflète une prédiction temporelle davantage liée à l'attente du stimulus qu'au programme moteur utilisé. Étant donné que cette prédiction est altérée chez les individus atteints de SZ, nous nous attendons à reproduire les altérations observées dans la littérature concernant les amplitudes de CNV chez ces individus.

Notons que le petit nombre de participants testés ne nous permet pas encore d'évaluer de manière fiable les trajectoires motrices. Par conséquent, nous ne pouvons pas examiner une éventuelle dissociation entre les prédictions liées à la trajectoire motrice et celles associées aux réponses après le signal cible. Nous nous concentrons donc uniquement sur les prédictions liées à la réponse au signal cible et celles révélées par les signaux EEG.

2. Matériels et Méthodes

2.1. Participants

Les caractéristiques démographiques des participants sont visibles dans le tableau 1 de la méthodologie générale (chapitre 2 – page 23). Concernant les caractéristiques cliniques, elles sont visibles dans le tableau 1 ci-dessous.

	Individus atteints de SZ	Neurotypiques
Traitement antipsychotique (typique/atypique/aucun)	2/4/1	-
Traitement antiparkinsonien (oui/non)	1/6	-
Traitement anticonvulsivant (oui/non)	1/6	-
Traitement antidépresseur (oui/non)	2/5	-
Traitement anxiolytique (oui/non)	1/6	-
Traitement benzodiazépine (oui/non)	1/6	-
Lithium (oui/non)	2/4	-
Score total SANS	34 ± 13	-
Score total SAPS	15 ± 13	-
Score QI fNart	104 ± 9	108 ± 5
Score total échelle Krebs	10 ± 2	3 ± 2

Tableau 1 : Caractéristiques cliniques des participants.

SANS : Échelle d'évaluation des symptômes négatifs (Andreasen, 1989). SAPS : Échelle d'évaluation des symptômes positifs (Andreasen, 1986). fNART : Test de lecture adulte national français (Mackinnon & Mulligan, 2005). Echelle Krebs : évaluation des signes neurologiques mineurs (Krebs et al., 2000).

Tous les individus atteints de SZ ont été diagnostiqués selon les critères du Manuel diagnostique et statistique des troubles mentaux (DSM) V (American Psychiatric Association, 2013). Les participants atteints de SZ ne devaient pas souffrir de troubles neurologiques ni d'autres troubles psychiatriques en dehors de la SZ. Ils ne devaient pas consommer de substance psychoactive autre que leur traitement.

Les individus neurotypiques ne devaient souffrir d'aucun trouble neurologique et ne devaient avoir aucun antécédent de maladie psychiatrique.

Pour tous les participants, la consommation de cannabis dans les 2 mois précédant l'expérience ou la consommation de toute substance psychotrope était un critère de non-inclusion. Les participants ayant des antécédents de traumatisme crânien avec une perte de connaissance de plus de 15 minutes n'ont pas été inclus.

Tous les participants ont donné leur consentement éclairé par écrit, et l'étude a été menée conformément à la Déclaration d'Helsinki. Le projet a été approuvé par le comité d'éthique régional de l'île de France (CPP Ile De France VII).

2.2. Équipement

Les participants étaient assis dans une pièce sombre et silencieuse, devant une boîte de 63 cm de hauteur, 60 cm de largeur et 47 cm de profondeur. Les participants devaient placer leur main dominante, poing fermé et index tendu, au contact de la surface à l'intérieur de la boîte. Un épais tissu noir recouvrait les ouvertures de la boîte, de sorte que pendant toute la durée des tâches, les participants ne pouvaient voir ni l'intérieur de la boîte ni leurs mouvements. Deux moteurs vibro-tactiles Precision Micro-Drives© étaient fixés sur l'avant-bras dominant de chaque participant : l'un en haut de l'avant-bras, sous le coude, et l'autre en bas de l'avant-bras, au-dessus du poignet. Ces moteurs fournissaient les stimuli tactiles indiquant aux participants quand démarrer/arrêter des mouvements linéaires à l'intérieur de la boîte.

Les tâches et les moteurs étaient contrôlées par un ordinateur Dell modèle OptiPlex 9020 AIO branché à un boîtier de stimulation Chronos E-Prime 3.0. L'intensité des vibrations

était réglée à 3,0 V, avec une fréquence de 230 Hz. Des bouchons d'oreilles en caoutchouc étaient fournis aux participants pour éviter qu'ils n'entendent les vibrations.
Une GoPro HERO7 était positionnée à l'intérieur de la boîte, suffisamment haut pour capturer toute la surface de la boîte. Elle filmait les trajectoires de l'index des participants, rendues visibles grâce à une LED rouge fixée sur leur ongle. Les paramètres d'enregistrement étaient : champ de vision linéaire, résolution de 120 Hz et un format plein écran HD 16:9.

2.3. Procédure

Notre protocole comprenait trois tâches expérimentales : les deux tâches motrices d'intérêt, et une tâche contrôle.

Dans les deux tâches motrices, les participants devaient démarrer un mouvement linéaire au contact de la surface de la boîte avec leur index dès l'occurrence d'une vibration tactile au coude (signal de départ) et l'arrêter le plus rapidement possible dès l'occurrence d'une vibration au poignet (signal cible) après un délai de 1000 ms (court) ou de 1700 ms (long).

Pour rappel, les deux tâches motrices diffèrent par la direction des mouvements effectués. Dans la tâche unidirectionnelle, les participants reviennent à la position de départ avant le début de l'essai suivant, de sorte que les mouvements étaient tous effectués dans la même direction. Dans la tâche multidirectionnelle, à chaque essai, le mouvement devait toujours être effectuer un mouvement dans une direction différente de celle du précédent. Les mouvements étaient restreints aux axes X et Y (directions horizontale et verticale).

Dans la tâche contrôle, les mêmes stimuli que dans les tâches motrices ont été utilisés, mais les consignes étaient similaires aux tâches classiques d'attente temporelle. Les participants devaient rester immobiles pendant la période d'attente, et réagir le plus rapidement possible à l'occurrence du signal cible (la vibration au poignet) en appuyant sur le bouton central d'un boîtier de réponse Chronos E-Prime 3.0.

Chaque tâche expérimentale comprenait un total de 240 essais, répartis en deux conditions : 120 essais avec un délai court et 120 avec un délai long. L'ordre dans lequel

les essais étaient présentés aux participants était aléatoire. Pour rendre le début de chaque essai imprévisible, nous avons utilisé un ITI variable allant de 2000 à 2300 ms.

Avant de commencer chaque tâche, une phase d'entraînement de 10 essais a été réalisée pour familiariser les participants avec les tâches. Pour les tâches motrices, l'expérimentateur profitait de cette phase d'entraînement pour s'assurer que les participants initiaient leur mouvement avec le signal de départ et s'arrêtaient avec le signal cible (et pas l'inverse). La vitesse de leurs mouvements était également surveillée visuellement afin d'éviter qu'ils n'aillent trop vite et ne touchent le bord de la boîte, ou trop lentement, ce qui aurait pu entraîner une trajectoire saccadée. Parfois, certains participants heurtaient un côté de la boîte. Dans ce cas, l'instruction était de s'arrêter complètement et de rester immobile jusqu'au prochain essai. Cette instruction nous permettait d'identifier ces essais comme des anticipations, ce qui nous a permis de les exclure de l'analyse ultérieure.

Une phase d'entraînement de 10 essais a aussi été réalisée avant la tâche contrôle. Pendant cette phase, l'expérimentateur s'est assuré que les participants avaient bien assimilé les instructions de la tâche et notamment qu'ils attendaient bien l'occurrence du signal cible pour appuyer sur le bouton-réponse.

2.4. EEG

Pendant la réalisation des tâches expérimentales, l'activité EEG a été enregistrée à l'aide du système ActiveTwo de Biosemi (Amsterdam, Pays-Bas), avec 64 électrodes actives Ag/AgCl disposées selon le système international 10-20. L'électrode de référence était constituée des électrodes Common Mode Sense (CMS) et Driven Right Leg (DRL). La qualité d'acquisition a été garantie en maintenant la tension moyenne de différence par rapport à l'électrode de référence (CMS) en dessous de 50 mV. Des électrodes ont été placées sur les lobes d'oreille gauche et droite pour le futur re-référencement du signal. Aucun filtre n'a été appliqué pendant l'acquisition de l'enregistrement, et le signal a été échantillonné à 2048 Hz.

Ce système EEG utilise des électrodes actives qui fonctionnent de la manière suivante : l'impédance d'entrée est très élevée (300 Mohm), tandis que l'impédance de sortie est très

faible (< 1 Ohm). Cela permet aux courants d'interférence de passer facilement sans créer de tensions d'interférence importantes.

2.5. Vidéos

Dans les deux tâches motrices, nous avons filmé les trajectoires des participants et analysé les vidéos collectées avec MATLAB 2021b.

La première étape consistait à segmenter les vidéos en essais (240 essais de 3 secondes). Le début de chaque essai était défini par l'occurrence du signal de départ (la vibration tactile sous le coude), enregistré par la caméra grâce à une LED bleue à l'intérieur de la boîte qui s'allumait au début de la vibration et durait 100 ms, soit jusqu'à la fin de la vibration. De même, pour rendre l'occurrence du signal cible (la vibration tactile au poignet) visible, une LED verte à l'intérieur de la boîte s'allumait pendant toute la durée de la vibration.

Nous avons analysé la trajectoire du doigt (de la LED) avec MATLAB. Nous avons établi plusieurs critères pour permettre à notre script d'analyse d'identifier le moment auquel les participants arrêtaient leur trajectoire. Les critères sont décrits dans la méthodologie du manuscrit principal de l'étude 1 (chapitre 3 page 30).

Ce point d'arrêt nous permettait de calculer la latence d'arrêt des participants, c'est-à-dire le délai nécessaire pour arrêter leur mouvement après l'occurrence du signal cible. La latence d'arrêt a été utilisée comme TR dans notre protocole. Le TR est l'indicateur couramment utilisé pour évaluer les performances des participants dans les tâches d'attente temporelle et nous a permis d'extrapoler les indicateurs comportementaux typiques des capacités de prédiction temporelle dans nos deux tâches motrices. Dans les deux tâches expérimentales, le point d'arrêt était défini comme le premier point où tous nos critères (décrits dans la méthodologie du manuscrit principal de l'étude 1 chapitre 3 – page 30) étaient remplis.

2.6. Analyses de données comportementales

Dans les deux tâches motrices, si aucun point ne satisfaisait les critères d'arrêt, il était considéré que les participants ne s'étaient pas arrêtés (erreur d'omission), et l'essai était exclu des analyses ultérieures.

Dans la tâche contrôle, les essais avec des erreurs d'omission ont également été exclus. Pour toutes les tâches, une réponse (arrêt du mouvement pour les tâches motrices et appui sur le bouton-réponse pour la tâche contrôle) survenant avant 150 ms après le début du signal cible était considérée comme anticipée et exclue des analyses.

		Tâches expérimentales		
Groupes	Conditions	Multidirectionnelle	Unidirectionnelle	Contrôle
Individus atteints de SZ	Court	9	17	4
	Long	25	34	8
Neurotypiques	Court	4	4	4
	Long	15	10	19

Tableau 2 : Nombre moyen d'essais exclus des analyses comportementales en fonction de la condition et de la tâche expérimentale chez les individus atteints de SZ et les neurotypiques. Pour rappel, chaque tâche contenait 240 essais, dont 120 pour la condition courte et 120 pour la condition longue.

La tâche unidirectionnelle est la seule où l'on a observé une différence significative dans le nombre d'essais entre les groupes expérimentaux ($W = 49.5$, $p = .01$, $r = 0.64$). Cette différence est due à un nombre moyen plus élevé d'arrêts anticipés chez les individus atteints de SZ (9 ± 11) en comparaison des individus neurotypiques (2 ± 4) ($W = 189$, $p < .001$, $r = 0.50$).

2.6.1. Indices des capacités de prédiction temporelle

Notre échantillon étant petit, pour rendre notre mesure plus sensible à la détection des marqueurs de capacités de prédiction temporelle (bénéfice du passage du temps et effets

séquentiels), dans nos analyses nous avons utilisé les indices décrits ci-dessous (Foerster & Joos et al., 2024), plutôt que les TRs bruts, comme variable dépendante.

Un effet de surprise ralentit les TRs dans la séquence long-court spécifiquement, ce qui entraîne un ralentissement du TR dans la condition courte. Ce ralentissement peut, par conséquent, accroître de manière artificielle la différence de TR entre les conditions courte et longue. Pour neutraliser l'influence du délai précédent sur le TR de l'essai actuel, Foerster et Joos et al. (2024) ont considéré uniquement des essais successifs avec des délais identiques. Dans ce cas, ils ont observé que le bénéfice du passage du temps sur les TRs (la diminution des TRs dans la condition longue par rapport à la condition courte) ne persistait pas chez les individus atteints de SZ.

Pour vérifier si les TRs étaient plus rapides en condition longue que courte (bénéfice du passage du temps), nous avons suivi la méthode proposée par Foerster et Joos et al., (2024). Nous avons calculé la différence de TR entre conditions courte et longue pour chaque participant, en analysant uniquement les essais avec le même délai que l'essai précédent (court-court et long-long). Ensuite, nous avons divisé cette différence par la somme des TRs pour tenir compte de la variabilité inter-individuelle des TRs. La formule était :

$$\frac{TR_{court-court} - TR_{long-long}}{TR_{court-court} + TR_{long-long}}$$

Plus l'indice positif est grand plus il indique un bénéfice du passage du temps important. Pour vérifier la présence d'effets séquentiels sur les TRs, nous avons appliqué la même logique. Pour rappel, les effets séquentiels se traduisent par des TRs au délai court plus lents lorsque le délai de l'essai précédent était long plutôt que court. Nous avons calculé, pour chaque participant, la différence de TR entre les essais avec un délai court précédé d'un délai long (séquence long-court) et ceux précédés d'un délai court (séquence court-court). Cette différence a ensuite été divisée par la somme des TRs des deux séquences. Notre formule était :

$$\frac{TR_{long-court} - TR_{court-court}}{TR_{long-court} + TR_{court-court}}$$

Plus l'indice positif est grand plus les effets séquentiels sont importants.

2.7. Analyse de données EEG

Les analyses EEG ont été réalisées sur MATLAB R2021b avec la toolbox EEGlab (Delorme & Makeig, 2004). Les étapes de prétraitement décrites ci-dessous ont été appliquées à chaque participant et pour chaque tâche séparément. D'abord, nous avons référencé notre signal avec des électrodes bipolaires attachées aux oreilles droite et gauche. Ensuite, nous avons réduit la fréquence d'échantillonnage de 2048 à 512 Hz pour maintenir une bonne résolution temporelle tout en réduisant le temps d'analyse. Les données ont été filtrées entre 0,01 et 30 Hz (Mento, 2017). Nous avons ensuite appliqué des étapes supplémentaires de nettoyage et de filtrage pour optimiser le jeu de données pour l'algorithme ICA 'runica' proposé par EEGlab (Luck, 2022). En moyenne, 2 ± 3 électrodes ont été interpolées pour les neurotypiques et 1 ± 1 pour les individus atteints de SZ. La segmentation des essais a été réalisée sur une fenêtre temporelle de 200 ms avant l'apparition du signal de départ à 2000 ms après, soit [-200 2000] ms. La ligne de base a été définie comme la moyenne du signal EEG de 200 ms avant l'apparition du signal de départ jusqu'à son début, soit [-200 0] ms. Les essais contenant des artefacts (signal ± 150 µV dans la fenêtre [-200 1700] ms) ont été exclus des analyses.

		Tâches expérimentales		
Groupes	Conditions	Multidirectionnelle	Unidirectionnelle	Contrôle
Individus atteints de SZ	Court	13	23	10
	Long	14	24	11
Individus neurotypiques	Court	9	10	6
	Long	9	9	8

Tableau 3 : Nombre moyen d'essais exclus des analyses EEG en fonction de la condition et de la tâche expérimentale chez les individus atteints de SZ et les neurotypiques. Pour rappel, chaque tâche contenait 240 essais, dont 120 pour la condition courte et 120 pour la condition longue.

Pour 1 participant neurotypique, les données étaient trop bruitées en raison d'artéfacts de transpiration et ont été exclues des analyses. Ceci ramène le groupe de neurotypiques à 7 participants pour les données EEG.

La première étape de nos analyses consistait à vérifier la présence d'une CNV entre 800 et 1000 ms, juste avant l'apparition du signal cible au délai court. Dans cette fenêtre temporelle, les participants ne savent pas encore si le délai sera court ou long, ce qui nous a permis de moyenner tous les essais sans distinction au sein de chaque tâche. Nous avons centré notre analyse sur les électrodes FCz, FC1 et C1, traditionnellement utilisées pour observer la CNV (Kononowicz & Penney, 2016; Kononowicz & Van Rijn, 2014; Mento et al., 2013).

Nous ne présentons pas les résultats concernant les effets séquentiels, étant donnés le petit nombre de participants par groupe, et le nombre réduit d'essais par condition dans cette analyse (le nombre d'essais est divisé par 2 par rapport au passage du temps).

3. Résultats

3.1. Comportementaux

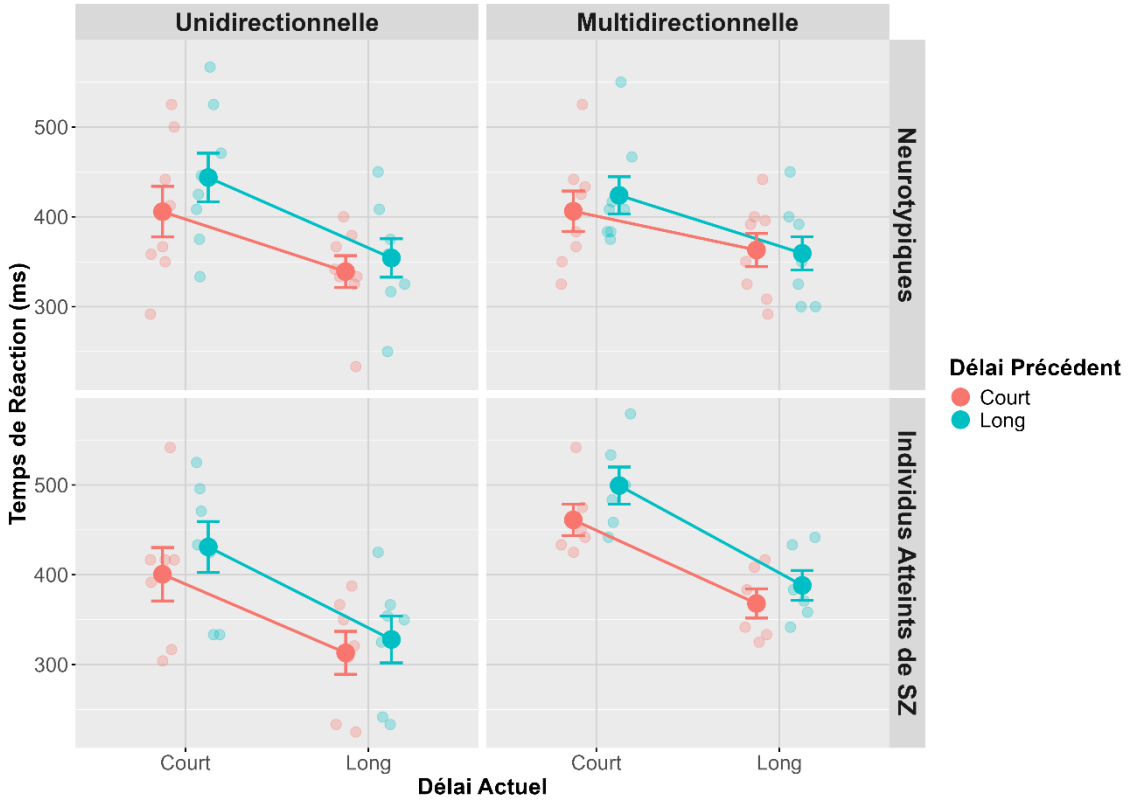

Figure 1. Les TRs en ms en fonction du délai de l'essai actuel, dans les deux tâches motrices sont présentés en fonction du groupe et du délai précédent. Les formes opaques avec barres d'erreur représentent les TRs moyens ± SEM, tandis que les formes transparentes montrent les données individuelles des participants pour chaque condition.

3.1.1. Tâche multidirectionnelle

Les analyses descriptives ci-dessous réfèrent à la figure 1.

Les individus atteints de SZ ont un TR globalement plus lent (429 ms ± 68.0) que les neurotypiques (388 ms ± 61.0).

Nous avons vérifié le bénéfice du passage du temps sur les TRs, indicateur de la prédiction temporelle. Pour rappel, les TRs sont plus rapides après un délai long qu'un délai court, ce qui a été observé chez tous les participants. Les individus atteints de SZ, ont un TR de 378 ms ± 39.9 au délai long, contre 480 ms ± 49.0 au délai court (différence de 102 ms). Chez les neurotypiques, le TR est de 361 ms ± 50.6 au délai long, contre 415 ms ± 59.7 au délai court (différence de 54 ms). Un indice du bénéfice du passage du temps a été calculé, afin d'éviter d'observer un ralentissement artificiel des TRs au délai court lorsque

précédé d'un délai long, dû à l'effet de surprise caractéristique des effets séquentiels. Cet indice est positif chez nos deux groupes expérimentaux avec un indice de 0.09 ± 0.04 chez les individus atteints de SZ et de 0.06 ± 0.05 chez les individus neurotypiques.

Nous avons également vérifié les effets séquentiels sur les TRs. Pour rappel, les TRs sont plus lents lorsqu'un délai court suit un délai long que lorsque deux délais courts se suivent. Au délai court, les individus atteints de SZ ont un TR plus lent après un délai long (499 ms ± 50.6) qu'après un délai court (461 ms ± 43.0) (différence de 38 ms). Chez les individus neurotypiques, le TR au délai court est légèrement plus lent si le délai précédent était long (424 ms ± 58.5) que s'il était court (406 ms ± 63.6) (différence de 18 ms). Cet effet séquentiel est présent uniquement chez les individus atteints de SZ, avec un indice d'effets séquentiels positif (0.04 ± 0.02) dans ce groupe.

3.1.2. Tâche unidirectionnelle

Les analyses descriptives ci-dessous réfèrent à la figure 1.

Les individus atteints de SZ ont un TR moyen légèrement plus rapide (368 ms ± 84.1) que les individus neurotypiques (386 ms ± 77.1) dans la tâche unidirectionnelle.

Concernant le bénéfice du passage du temps, tous les participants arrêtent leur mouvement plus rapidement aux délais longs que courts. Chez les individus atteints de SZ, le TR est de 321 ms ± 64.0 au délai long contre 416 ms ± 75.5 au délai court (différence de 95 ms). Pour les neurotypiques, le TR est de 347 ms ± 54.2 au délai long contre 425 ms ± 77.9 au délai court (différence de 78 ms). Cet indice est positif dans les deux groupes expérimentaux, avec une valeur de 0.10 ± 0.04 chez les individus atteints de SZ et de 0.07 ± 0.06 chez les individus neurotypiques.

Concernant les effets séquentiels, cette tâche montre que, chez tous les participants, le TR au délai court est plus lent lorsque le délai précédent était long, plutôt que court. Pour les individus atteints de SZ, le TR au délai court est de 431 ms ± 75.0 lorsque le délai précédent était long, comparé à 401 ms ± 78.6 lorsqu'il était court. Chez les individus neurotypiques, ces chiffres sont respectivement de 444 ms ± 76.5 et 406 ms ± 79.6. L'effet

séquentiel est positif dans les deux groupes, avec un indice de 0.04 ± 0.03 chez les individus atteints de SZ et de 0.05 ± 0.04 chez les neurotypiques.

3.1.3. Tâche contrôle

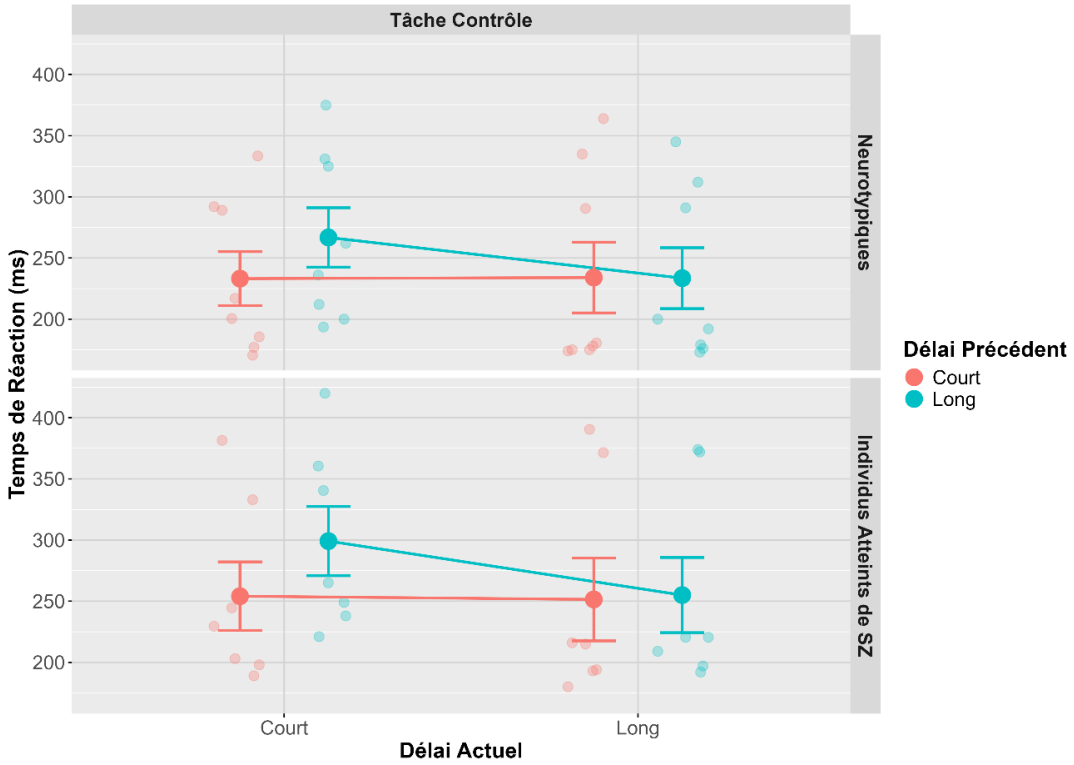

Figure 2. Les TRs en ms en fonction du délai de l'essai actuel dans la tâche contrôle sont présentés en fonction du groupe et du délai précédent. Les formes opaques avec barres d'erreur représentent les TRs moyens ± SEM, tandis que les formes transparentes montrent les données individuelles des participants pour chaque condition.

Les analyses descriptives ci-dessous réfèrent à la figure 2.

Les individus atteints de SZ ont un TR global plus lent (265 ms ± 78.3) que les individus neurotypiques (242 ms ± 69.2) dans la tâche contrôle. Ce résultat reproduit les données de la littérature selon lesquelles les individus atteints de SZ ont des TRs généralement plus lents que les individus neurotypiques dans les tâches d'attente temporelle classiques (Ciullo et al., 2018).

En accord avec le principe du bénéfice du passage du temps, tous les participants réagissent plus rapidement au délai long comparativement au délai court. Pour les

individus atteints de SZ, les TRs sont de 253 ms ± 82.2 au délai long contre 277 ms ± 75.4 au délai court (différence 24 ms). Chez les individus neurotypiques, les TRs sont de 234 ms ± 73.7 au délai long et de 250 ms ± 65.8 au délai court (différence 16 ms).

Concernant les effets séquentiels, chez tous les participants, le TR au délai court est plus lent lorsque le délai précédent était long, plutôt que court. Pour les individus atteints de SZ, le TR au délai court est de 299 ms ± 74.8 lorsque le délai précédent était long, comparé à 254 ms ± 74.3 lorsqu'il était court. Chez les individus neurotypiques, ces chiffres sont respectivement de 267 ms ± 68.7 et 233 ms ± 62.5. L'effet séquentiel est positif dans les deux groupes, avec un indice de 0.09 ± 0.06 chez les individus atteints de SZ et de 0.07 ± 0.01 chez les neurotypiques.

3.2. EEG

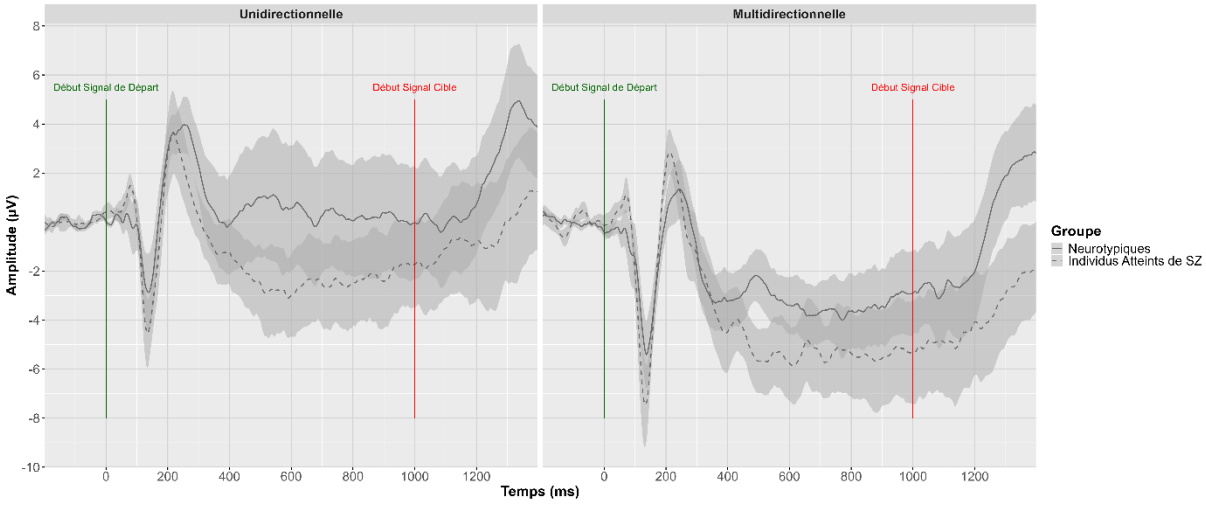

Figure 3. Amplitudes de la CNV en µV dans les deux tâches motrices, en fonction du groupe et moyennées sur trois électrodes (FCz, FC1 et C1) pour tous les essais actuels (indépendamment du délai auquel le signal cible intervient). La zone ombrée autour des courbes correspond à l'erreur standard de la moyenne (SEM). Le point 0 ms sur l'axe des abscisses marque le début du signal de départ (ligne verte), tandis que le point 1000 ms marque l'occurrence du signal cible pour le délai court (ligne rouge).

3.2.1. Tâche multidirectionnelle

Les individus atteints de SZ présentent une CNV d'amplitude -5.4 µV ± 4.7 dans la fenêtre temporelle 800-1000 ms (Figure 3).

Chez les individus neurotypiques, l'amplitude de la CNV est de -3.3 µV ± 4.2 dans la fenêtre temporelle de 800-1000 ms, ce qui est moins négatif que ce qui est observé chez les individus atteints de SZ (Figure 3).

3.2.2. Tâche unidirectionnelle

Dans la tâche unidirectionnelle, dans la fenêtre temporelle de 800-1000 ms, l'amplitude de la CNV des individus atteints de SZ est plus négative (-2.1 µV ± 4.4) que celle des neurotypiques (0.2 µV ± 6.3) (Figure 3).

3.2.3. Tâche contrôle

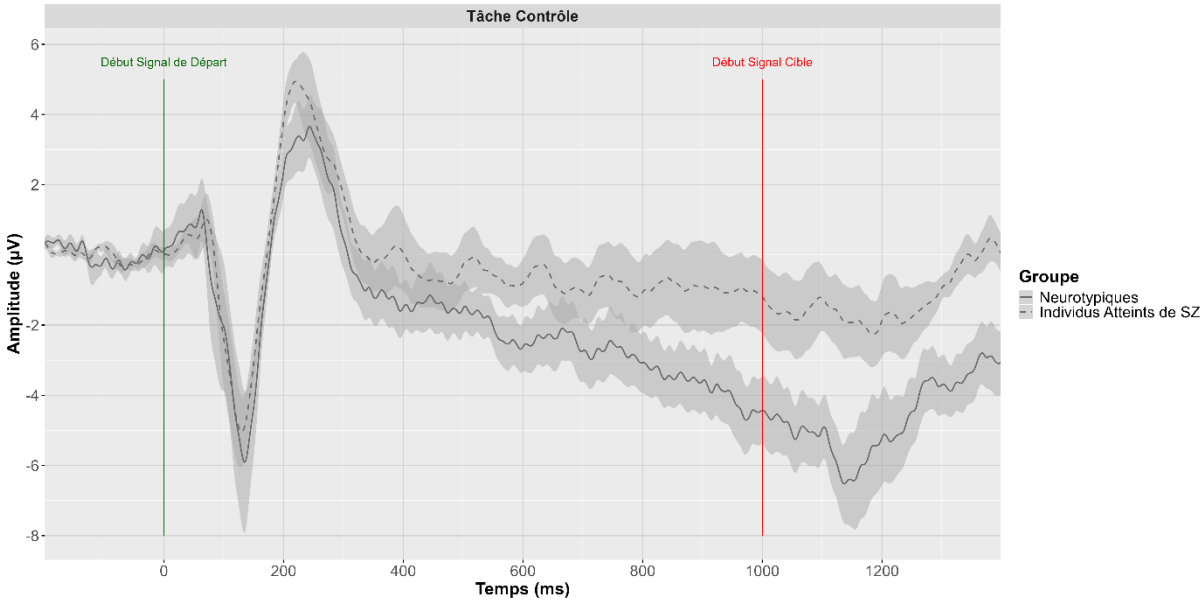

Figure 4. Amplitudes de la CNV en µV dans la tâche contrôle, en fonction du groupe et moyennées sur trois électrodes (FCz, FC1 et C1) pour tous les essais actuels (indépendamment du délai auquel le signal cible intervient). La zone ombrée autour des courbes correspond à l'erreur standard de la moyenne (SEM). Le point 0 ms sur l'axe des

abscisses marque le début du signal de départ (ligne verte), tandis que le point 1000 ms marque l'occurrence du signal cible pour le délai court (ligne rouge).

Chez les individus atteints de SZ, l'amplitude de la CNV dans la fenêtre 800-1000 ms est de -0.9 μV ± 2.7, contre -3.8 μV ± 2.4 chez les neurotypiques (Figure 4).

4. Discussion

L'objectif de l'étude présente était de vérifier si la prédiction temporelle spécifiquement liée à une action motrice est préservée ou altérée dans la SZ. Nous avons utilisé des tâches d'attente temporelle dans lesquelles les participants devaient effectuer un mouvement continu et l'arrêter le plus rapidement possible après un signal cible. Deux tâches ont été utilisées : la tâche multidirectionnelle, où les participants changeaient de direction à chaque essai, et la tâche unidirectionnelle, où ils allaient toujours dans la même direction. Dans cette dernière, aller dans la même direction permet de réutiliser le même programme moteur et de tirer parti des informations temporelles associées au mouvement précédent pour ajuster son mouvement à l'essai actuel. Nous avons également utilisé une tâche classique d'attente temporelle, où les participants restaient immobiles pendant l'attente et appuyaient sur un bouton-réponse à l'apparition de la cible. Cette tâche a été utilisée comme condition contrôle car elle correspond aux protocoles utilisés dans la littérature (Klemmer, 1956; Los, 2010; Niemi & Näätänen, 1981; Vallesi et al., 2013).

Dans les trois tâches expérimentales, nous avons recueilli les réponses comportementales (TRs) et EEG (CNV) des participants. Dans les deux tâches motrices, il y avait un bénéfice du passage du temps similaire dans les deux groupes sur le comportement. De plus, nous avons observé une CNV plutôt plus claire chez les individus atteints de SZ que chez les neurotypiques. Dans la tâche contrôle, le bénéfice du passage du temps mesuré sur les réponses comportementales est d'amplitude trop faible pour tirer des conclusions. Cependant, les résultats EEG ont révélé la différence d'amplitude de CNV attendue entre les individus neurotypiques et ceux atteints de SZ (Osborne et al., 2020). Bien que notre interprétation doive rester prudente en raison de notre petit échantillon, ces résultats suggèrent que la réalisation d'un mouvement pendant l'attente pourrait rétablir le bénéfice du passage du temps observable sur la CNV et les TRs chez les individus atteints de SZ,

ce qui constitue une observation nouvelle dans la littérature, et a représenté une surprise. L'une des explications possibles est que le caractère continu du mouvement pourrait rétablir la continuité du passage du temps, parce que le mouvement est nécessairement continu. Une alternative est que la tâche motrice oblige les individus atteints de SZ à prédire leur action et à en vérifier l'exécution, c'est-à-dire à vérifier le retour sensoriel.

Dans les tâches d'attente temporelle, la CNV a été d'abord décrite comme un potentiel évoqué par un premier stimulus qui persiste jusqu'à l'occurrence d'un stimulus cible (Walter et al., 1964). Lorsque ce stimulus cible nécessite une réponse motrice, il a été proposé que la CNV reflète une préparation temporelle associée à des processus perceptuels et moteurs, tous deux chronométrés : le stimulus apparaît à un moment donné et il faut y réagir rapidement (Los & Heslenfeld, 2005; Macar & Besson, 1985; Mento, 2013, 2017). La CNV se distingue d'autres potentiels évoqués moteurs en ce qu'elle reflète une préparation motrice initiée par un stimulus externe. Elle reflèterait des processus sensorimoteurs plutôt que des processus moteurs purs (Brunia, 2003; Brunia et al., 2011). Une différence d'amplitude de CNV entre les tâches motrices et la tâche contrôle pourrait refléter une différence d'intégration sensorimotrice pendant l'attente entre nos deux types de tâches.

L'intégration sensorimotrice est le processus par lequel les signaux sensoriels provenant du corps et de l'environnement sont utilisés pour ajuster le comportement moteur (Wolpert et al., 1998). Ce processus est étroitement lié au traitement temporel, car il est essentiel de connaître le moment précis où les informations sensorielles se produisent pour permettre une adaptation efficace du comportement moteur (Conte et al., 2017; Lee et al., 2018). Les informations sensorielles sont utilisées à la fois lors de la planification et de l'exécution motrice. Pendant la planification, elles (1) informent sur la position actuelle du corps (état de référence) et (2) prédisent l'état cible à atteindre par le mouvement. La comparaison entre ces deux états permet de planifier les commandes motrices nécessaires pour atteindre l'état cible. Cette comparaison doit se faire tout le long du mouvement, pour ajuster le geste (Aschersleben, 2002; Desmurget & Grafton, 2000; Drewing & Aschersleben, 2003; LaRue, 2005; Wolpert et al., 1995). Soit le geste lui-même, soit les vérifications sensorielles, pourraient pallier la fragilité du passage du temps chez les individus atteints de SZ.

Dans la tâche contrôle à l'inverse, les participants ne bougent pas pendant l'attente et doivent préparer leur réponse à l'occurrence du stimulus cible. Sans tenir compte des informations temporelles issues des essais précédents (effets séquentiels), la seule information disponible pour actualiser la préparation motrice (la préparation à arrêter le mouvement) est le passage du temps. Selon les théories basées sur les probabilités de survenue des cibles, la probabilité d'occurrence du stimulus augmente avec le passage du temps, et le niveau de préparation des participants devrait augmenter en conséquence (Correa et al., 2006; Mento, 2017; Niemi & Näätänen, 1981; Nobre et al., 2007). Cette préparation temporelle influence l'amplitude de la CNV chez les individus neurotypiques, mais pas chez les individus atteints de SZ dans notre tâche contrôle. Cela corrobore des résultats récents (Foerster & Joos et al., 2024). C'est donc bien l'action motrice elle-même qui permettrait de compenser les difficultés des individus atteints de SZ.

Bien que cette interprétation soit cohérente avec nos hypothèses initiales, elle ne permet pas, à ce stade, de distinguer le rôle de la vérification sensorielle de celui de la prédiction motrice dans la restauration du bénéfice du passage du temps sur les performances. Ces mécanismes pourront être distingués avec un échantillon de participants plus grand, en analysant les caractéristiques de la trajectoire et en les comparant dans les taches uni- et multidirectionnelles. Si la trajectoire elle-même n'est pas affectée (Delevoye-Turrell et al., 2007), des effets séquentiels pourraient n'être présents que sur la réponse au signal cible, mais pas sur la trajectoire elle-même. Ceci suggérerait un profil de résultat similaire à ceux observés chez les enfants et les adolescents neurotypiques de l'étude 2. La SZ est un trouble neurodéveloppemental, rendant cette hypothèse plausible.

En conclusion, cette étude a examiné les mécanismes de prédiction temporelle liés à l'action motrice chez les individus atteints de SZ à travers différentes tâches d'attente temporelle. Les résultats indiquent que, dans les tâches motrices, les performances comportementales et EEG des individus atteints de SZ bénéficient du passage du temps de manière similaire aux neurotypiques. Cela suggère que l'exécution d'un mouvement continu pendant l'attente pourrait rétablir ce bénéfice chez les individus atteints de SZ. Nous supposons que cette restauration est liée aux vérifications sensorielles effectuées lors de l'exécution du mouvement, ou possiblement à l'exécution elle-même. Ces hypothèses pourront être explorées dans un échantillon plus large.

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Rappel des résultats principaux de l'étude 4

L'étude 4 avait pour objectif d'examiner les mécanismes de prédiction temporelle associés à la planification et à l'exécution d'un mouvement chez les individus atteints de SZ. Pour cela, nous avons utilisé deux tâches motrices : la tâche multidirectionnelle et la tâche unidirectionnelle, en recueillant les TRs et les potentiels évoqués (CNV) des participants, comprenant des individus atteints de SZ et des neurotypiques. Nous avons également employé une tâche contrôle d'attente temporelle, qui s'apparente davantage aux protocoles de la littérature, car elle n'impliquait pas de mouvement pendant la période d'attente, et la réponse au signal cible consistait simplement en un appui sur un bouton réponse.

Dans nos deux tâches motrices, nous avons observé un bénéfice du passage du temps sur les TRs, avec des arrêts du mouvement plus rapides au délai long par rapport au délai court, et ce pour tous les participants, quel que soit leur groupe. En revanche, dans la tâche contrôle, le bénéfice du passage du temps observé sur les réponses comportementales était d'une amplitude trop faible pour permettre des conclusions significatives.

Concernant les résultats EEG, nous avons observé dans nos deux tâches motrices qu'avant l'occurrence du signal cible au délai court, les amplitudes de CNV étaient équivalentes entre les individus atteints de SZ et les neurotypiques. Cette observation est nouvelle dans la littérature. A l'inverse dans la tâche contrôle, nous avons constaté une amplitude de CNV plus négative chez les neurotypiques par rapport aux individus atteints de SZ, ce qui reproduit les altérations décrites dans la littérature.

Ces résultats suggèrent que la réalisation d'un mouvement pendant la période d'attente pourrait permettre de rétablir le bénéfice du passage du temps, tant sur les indicateurs comportementaux que EEG, chez les individus atteints de SZ.

7. DISCUSSION GÉNÉRALE

Notre travail nous a conduit à questionner un aspect particulier de l'intégration sensorimotrice, à savoir l'intégration de la prédiction liée à l'occurrence d'un stimulus sensoriel dans le programme moteur, chez des individus neurotypiques, durant le développement, chez des individus à HR, et atteints de SZ.

Nous avons conçu de nouvelles tâches basées sur le principe des tâches d'attente temporelle, où les participants devaient initier un mouvement continu après un signal de départ et l'arrêter dès qu'un signal cible arrivait. Comme dans les tâches classiques d'attente temporelle, nous avons mesuré un TR, plus précisément la latence d'arrêt après la cible. Cette mesure a permis d'évaluer le bénéfice du passage du temps, observé par des TRs plus rapides lorsque la cible survient après un délai long comparé à un délai court. Nous avons également évalué les effets séquentiels, qui traduisent l'influence du délai de l'essai précédent sur l'essai actuel. Pour mémoire, à l'essai actuel si la cible survient à un délai plus court qu'à l'essai précédent, les TR sont ralentis.

L'ajout de la composante motrice pendant l'attente nous a permis de quantifier également la préparation en anticipation de l'arrêt du mouvement. Pour ce faire, nous avons calculé des pentes relatives de décélération en comparant la vitesse au moment du ralentissement à celle juste avant le signal cible : (vitesse au point de décélération – vitesse avant le signal cible) / vitesse au point de décélération. Afin de tester dans quelle mesure la prédiction temporelle est intégrée au programme moteur, nous avons analysé les effets séquentiels sur l'indicateur de préparation de l'arrêt du mouvement. Deux types de tâches ont été développés : dans la tâche unidirectionnelle, la trajectoire était la même à chaque essai, tandis que dans la tâche multidirectionnelle, les participants changeaient de direction.

Nous commencerons par présenter les principaux résultats de nos études, suivis d'une discussion sur deux questions émergentes de notre recherche. La première concerne la dissociation des mécanismes de prédiction temporelle opérant à la même échelle temporelle, tandis que la seconde porte sur l'intégration sensorimotrice.

7.1. La prédiction temporelle motrice

7.1.1. Étude 1 chez les neurotypiques adultes

Lors de notre étude 1, des effets séquentiels sur la décélération, et plus exactement sur les pentes relatives de décélération ont été observés uniquement dans la tâche unidirectionnelle. Lorsque la cible survenait à un délai court, les participants ralentissaient plus efficacement lorsque le délai précédent était également court, plutôt que long : ils partaient d'une vitesse plus élevée et effectuaient un ralentissement plus abrupt. Ces résultats suggèrent que, dans la tâche unidirectionnelle, les participants anticipaient mieux l'arrêt du mouvement au délai court en ajustant leur décélération de façon plus efficace à l'approche du signal cible quand le délai précédent était également court. Nous n'avons observé aucun effet séquentiel sur cet indicateur avant le délai long, reproduisant ainsi l'asymétrie des effets séquentiels rapportés dans la littérature (Correa et al., 2006b; Los et al., 2014; Mento, 2017; Niemi & Näätänen, 1981; Vallesi et al., 2013).

La dichotomie observée concernant les effets séquentiels entre nos deux tâches motrices s'est également manifestée sur les TRs. Dans la tâche unidirectionnelle, nous avons observé des effets séquentiels, se traduisant par un arrêt du mouvement plus lent au délai court lorsque le délai précédent était long plutôt que court. Ce ralentissement du TR en fonction du délai précédent était asymétrique : au délai long, le TR restait stable, quel que soit le délai précédent. Ces effets séquentiels sur le TR, largement documentés dans la littérature, constituent un indicateur robuste et automatique des capacités de prédiction temporelle (Brulé et al., 2021; Kong et al., 2015; Los, 2010; Steinborn et al., 2008; Vallesi et al., 2014). En revanche, de manière inattendue, aucune influence du délai précédent sur l'arrêt au délai court n'a été observée dans la tâche multidirectionnelle.

L'absence d'effets séquentiels dans la tâche multidirectionnelle, où la direction change à chaque essai, contrastait avec leur persistance dans la tâche unidirectionnelle, où la direction est similaire d'un essai à l'autre. Cette dichotomie a été interprétée comme un argument selon lequel les effets séquentiels observés sur nos indicateurs comportementaux étaient dus à une prédiction temporelle intrinsèquement liée à une commande motrice spécifique. Ces résultats étaient distincts de ceux observés à l'EEG,

mais ces derniers seront abordés en fin de discussion, en parallèle avec les résultats préliminaires obtenus chez les individus atteints de SZ (étude 4).

7.1.2. Études 2 chez les neurotypiques, de l'enfance à l'âge adulte

Dans l'étude 2, menée sur une population de neurotypiques âgés de 9 à 24 ans, nous avons reproduit les résultats observés chez les adultes de l'étude 1 sur les pentes relatives de décélération. Exclusivement dans la tâche unidirectionnelle, nous avons observé un effet séquentiel sur les pentes relatives de décélération au délai court, avec un ralentissement plus rapide lorsque le délai de l'essai précédent était également court plutôt que long. La réplication de ces résultats indique que la prédiction temporelle est intégrée au programme moteur chez l'individu neurotypique dès l'âge de 9 ans, du moins en ce qui concerne le programme moteur planifié en amont de l'action et avant la survenue de la cible.

Cependant, sur les TRs, nous avons observé une dissociation intéressante par rapport aux résultats de l'étude 1. Chez les jeunes participants, des effets séquentiels ont été identifiés dans les deux tâches motrices, bien que leur intensité soit plus marquée dans la tâche unidirectionnelle. La présence de ces effets séquentiels dans la tâche où le programme moteur varie d'un essai à l'autre indique qu'ils ne dépendent pas nécessairement d'un programme moteur spécifique, du moins chez les jeunes.

Dans nos tâches, l'arrêt du mouvement est déclenché par l'occurrence du signal cible, ce qui suggère que les effets séquentiels chez les jeunes pourraient partiellement résulter de la prédiction de ce signal. Étant donné que ces effets ne peuvent être attribués uniquement à une prédiction temporelle associée à la commande motrice (étude 2) ni à une prédiction sensorielle isolée (étude 1), nous proposons qu'ils sont le fruit d'une prédiction temporelle sensorimotrice, laquelle semble évoluer avec le neurodéveloppement (Chicoine et al., 1992; Gordon-Murer et al., 2021; Viel et al., 2009). Chez l'adulte, nous avions interprété la persistance des effets séquentiels lors de la répétition du mouvement et leur disparition dans la condition multidirectionnelle comme un argument selon lequel l'intégration de la prédiction sensorielle se fait dans un programme moteur précis. En revanche, cette association ne semble pas aussi précise chez les jeunes neurotypiques, du moins quand il leur faut prendre en compte le retour sensoriel pour arrêter le mouvement.

Avant d'approfondir notre discussion sur l'intégration sensorimotrice, il nous paraît nécessaire de poursuivre notre discussion des résultats relatifs à la prédiction temporelle motrice, en particulier les effets séquentiels sur les pentes relatives de décélération. Les résultats obtenus chez les individus à HR de l'étude 3 concernant cet indicateur ont non seulement renforcé notre questionnement sur le rôle de l'intégration sensorimotrice dans notre protocole, mais ont également soulevé la possibilité d'une divergence dans la maturation de ce processus entre les populations neurotypiques et neuro-atypiques.

7.1.3. Étude 3 chez les individus à HR de conversion psychotique

Dans l'étude 3, nous avons observé un effet séquentiel sur les pentes relatives de décélération avant le délai court qui était plus fort dans la tâche unidirectionnelle que dans la tâche multidirectionnelle. Cependant, les résultats ont aussi montré des différences dans l'expression des effets séquentiels entre les groupes. L'analyse de la distribution des TRs a suggéré un effet séquentiel plus prononcé chez les individus à HR par rapport aux neurotypiques, sans interaction avec la tâche. Les individus à HR avaient également tendance à présenter un effet séquentiel plus marqué sur leurs pentes relatives de décélération avant le délai court, quel que soit le type de tâche motrice considéré. Ces observations pourraient indiquer que, chez les individus à HR, la prédiction temporelle observée durant la préparation motrice semble davantage dépendre d'une prédiction sensorielle externe, qui n'est pas liée au programme moteur exécuté. Ceci pourrait conduire à une inefficacité et à une imprécision de l'anticipation motrice chez cette population.

Les pentes relatives de décélération jouent un rôle important dans nos résultats. Ces pentes révèlent l'efficacité de la planification de l'arrêt du mouvement (Woodworth, 1899). Elles permettent ainsi de comparer les différentes stratégies de planification motrice. Les variations observées pourraient refléter une maturation distincte du contrôle moteur entre les groupes expérimentaux. Nous développons ce point dans le passage suivant.

7.2. Analyse de la planification motrice : neurotypiques vs. neuro-atypiques

Avant le délai court, dans la tâche unidirectionnelle, les individus à HR âgés de 13 à 17 ans ont montré des pentes relatives de décélération plus abruptes que les neurotypiques du même âge (étude 3). Ces pentes plus abruptes indiquent un ralentissement plus marqué dans un même laps de temps. Pour rappel, elles signent le fait que les individus à HR partent d'une vitesse élevée, mais parviennent à suffisamment ralentir pour atteindre une vitesse équivalente à celle des neurotypiques au moment d'arrêter leur mouvement. Grâce à ce ralentissement, les individus à HR réussissent à arrêter leur mouvement aussi efficacement que leurs homologues neurotypiques. Cela suggère qu'ils bénéficient de la répétition du programme moteur dans la tâche unidirectionnelle pour optimiser leur décélération et ainsi bien exécuter l'arrêt.

Ce phénomène est également observé chez les neurotypiques, mais âgés de 9 à 12 ans (étude 2). Ces derniers ont montré des pentes relatives de décélération plus abruptes que les neurotypiques âgés de 18 à 24 ans. Ces pentes plus abruptes permettaient aux 9 – 12 ans d'arrêter leur mouvement avec autant d'efficacité que les plus âgés. En cela, ces pentes abruptes sont un signe d'efficacité motrice.

Dans la tâche multidirectionnelle, le changement de commande motrice à chaque essai devrait limiter l'optimisation de la préparation de l'arrêt. C'est ce qui est observé chez les jeunes neurotypiques, dont les pentes relatives de décélération deviennent similaires à celles des participants plus âgés dans la tâche multidirectionnelle. En revanche, l'exécution de l'arrêt chez les jeunes n'est plus aussi efficace que celle des plus âgés, comme en témoignent leurs TRs plus lents au délai court dans cette tâche (étude 2), et signe une difficulté à réagir au signal sensoriel dans cette tâche motrice. À l'inverse, chez les individus à HR âgés de 13 à 17 ans, le changement de direction dans la tâche multidirectionnelle ne les empêche pas de montrer des pentes relatives de décélération plus abruptes que celles des neurotypiques. Cette stratégie s'avère inefficace, car elle ne permet pas d'optimiser l'exécution de l'arrêt dans cette tâche, comme en témoignent les TRs plus lents observés chez les individus à HR par rapport aux neurotypiques (étude 3).

Chez les individus à HR, une décélération abrupte dans la tâche multidirectionnelle pourrait révéler un déficit général de l'anticipation de l'arrêt, qui mène à une vitesse excessive pendant l'exécution du mouvement, et qui explique la pente abrupte de décélération. On pourrait s'interroger sur les liens entre ce comportement moteur et l'impulsivité motrice observée chez les individus à HR (Fekih-Romdhane et al., 2024; Lee et al., 2013), mais cette question nécessitera d'autres études.

Dans notre protocole, des anomalies ont été observées sur les TRs même chez les neurotypiques. L'arrêt du mouvement est déclenché par l'occurrence d'un signal cible, et bien préparer cet arrêt requiert de pouvoir anticiper ce signal et ajuster le mouvement quand il survient. L'intégration sensorimotrice joue un rôle central dans ce processus, permettant au système nerveux central de combiner les informations sensorielles et motrices pour générer des réponses adaptées (Bianco et al., 2024; Edwards et al., 2019; Wolpert et al., 1995). La divergence observée dans les stratégies de planification motrice entre les groupes pourrait refléter une différence dans leurs capacités d'intégration sensorimotrice. En grandissant, les neurotypiques perfectionnent cette capacité d'intégration, ce qui leur permet de ne plus dépendre d'un ralentissement excessif pour bien exécuter l'arrêt. À l'inverse, chez les individus à HR, cette maturation semble suivre une trajectoire différente, les obligeant à ralentir davantage pour compenser un déficit d'anticipation.

7.3. L'intégration sensorimotrice

Les capacités d'intégration sensorimotrice continuent de se développer tout au long de l'enfance et de l'adolescence, ce qui peut expliquer les variations observées dans la planification et l'exécution des réponses entre nos groupes expérimentaux (Chicoine et al., 1992; Gordon-Murer et al., 2021; Quatman-Yates et al., 2012; Viel et al., 2009). Par exemple, une intégration inadéquate de la prédiction du signal cible dans la préparation à l'arrêt pourrait entraîner une exécution moins efficace chez les plus jeunes.

L'ensemble de nos résultats nous a amené à interroger le rôle de l'intégration sensorimotrice, sujet que nous abordons dans la suite de la discussion concernant nos trois premières études.

7.3.1. Les effets séquentiels sur le TR : indicateurs d'une prédiction temporelle sensorimotrice

Pour rappel, dans l'étude 1, une dichotomie a été observée concernant les effets séquentiels sur les TRs. Comme pour les pentes relatives de décélération, ces effets séquentiels étaient présents dans la tâche unidirectionnelle, mais absents dans la tâche multidirectionnelle. Leur disparition avec le changement de commande motrice suggère qu'ils pourraient être liés à une prédiction temporelle dépendante du programme moteur.

Nous l'avons évoqué, les résultats de l'études 2 ont montré que les jeunes participants présentaient des effets séquentiels sur leurs TRs, indépendamment du type de tâches motrices. Ces résultats ont soulevé des questions sur la nature de la prédiction temporelle associée aux effets séquentiels sur les TRs et nous ont incité à explorer le rôle de l'intégration de la prédiction temporelle sensorielle dans la commande motrice (i.e. le rôle de l'intégration sensorimotrice) lors de l'exécution de la réponse.

7.3.1.1. Maturation des capacités d'intégration sensorimotrices chez les neurotypiques

La maturation des capacités d'intégration sensorimotrice se poursuit tout au long de l'enfance et de l'adolescence. La littérature suggère qu'une évolution asynchrone des systèmes sensoriels et moteurs pourrait être à l'origine d'une dissociation partielle de ces processus durant le neurodéveloppement (Bender et al., 2005; Flores et al., 2009; Gordon-Murer et al., 2021; Viel et al., 2009). Au fil du temps, les informations sensorielles sont progressivement intégrées au contrôle moteur, illustrant ainsi la maturation de l'intégration sensorimotrice. Ce développement pourrait expliquer pourquoi les performances motrices des adultes sont généralement plus précises et rapides que celles des jeunes (Adams & Lambos, 1986; Eckert & Eichorn, 1977; Johnson et al., 2015).

Dans notre étude 2, le jeune âge des participants pourrait expliquer la persistance des effets séquentiels sur les TRs dans la tâche multidirectionnelle. Chez les jeunes, la prédiction de l'occurrence du signal cible n'est peut-être pas intégrée à une commande motrice précise, ce qui pourrait expliquer la persistance de ces effets, même lorsque le mouvement change.

Attribuer la persistance de ces effets à un manque de maturité des capacités d'intégration sensorimotrice nécessite une discussion plus approfondie de la préservation de ces effets dans le groupe âgé de 18 à 24 ans. Cette tranche d'âge étant proche de celle des participants de l'étude 1, on pourrait s'attendre à des résultats similaires à ceux observés chez les adultes neurotypiques. Toutefois, plusieurs différences au sein de nos échantillons doivent être prises en compte.

Tout d'abord, le groupe de jeunes adultes de l'étude 2 comptait 12 participants contre 25 dans l'étude 1, ce qui pourrait entraîner une plus grande variabilité intra-groupe dans l'étude 2, en particulier concernant la maturation de l'intégration sensorimotrice. En effet, les participants âgés de 18 à 20 ans représentaient 20% du groupe de l'étude 1, contre 33% dans l'étude 2. Comme les capacités d'intégration sensorimotrice continuent de se développer jusqu'à environ 20 ans (Chicoine et al., 1992), cela pourrait accentuer les différences observées entre nos deux études.

De plus, bien que la proportion d'hommes soit similaire dans les deux études (25%), la différence de performances entre les sexes pourrait être plus marquée dans l'étude 2. En effet, des écarts de maturation sensorimotrice entre hommes et femmes ont été rapportés (Nolan et al., 2005; Viel et al., 2009), particulièrement prononcés jusqu'à au moins 18 ans (Largo et al., 2001).

Enfin, il est important de noter que les participants de l'étude 1 étaient français, tandis que ceux de l'étude 2 étaient canadiens. Les variations dans la maturation des processus sensorimoteurs peuvent être dues à des facteurs contextuels, parmi lesquels le système éducatif. Ce dernier est associé au développement cognitif et pourrait contribuer à cette maturation sensorimotrice (Kertész & Honbolygó, 2023). Ce dernier point souligne l'importance d'une représentation diversifiée dans les recherches pour assurer la reproductibilité des résultats.

7.3.1.2. La prédiction temporelle sensorimotrice chez les individus à HR de conversion psychotique

L'examen des TRs bruts a montré que les individus à HR de conversion psychotique ont montré des effets séquentiels uniquement dans la tâche unidirectionnelle (étude 3). Ce résultat était surprenant, car étant donné leur âge nous aurions pu nous attendre à des effets séquentiels dans les deux tâches motrices, comme chez les participants neurotypiques (étude 2). Pour mieux comprendre cette observation, nous avons analysé la distribution des TRs afin de vérifier si ces effets pouvaient être masqués par une différence dans la répartition des réponses chez les individus à HR par rapport aux neurotypiques.

Les analyses de l'asymétrie de la distribution des TRs au délai court ont révélé que les individus à HR présentaient une asymétrie vers des réponses plus lentes lorsque le délai précédent était long. Cette asymétrie n'était pas observée chez les neurotypiques. Ce résultat suggère que les individus à HR présentent un effet séquentiel plus marqué que les neurotypiques dans les deux tâches, mais masqué par une variabilité des réponses. Cela pourrait suggérer que les capacités d'intégration sensorimotrice des individus à HR sont moins matures que celles des neurotypiques, ce qui les rend plus sensibles aux effets séquentiels, notamment dans la tâche multidirectionnelle.

La littérature suggère déjà des troubles de l'intégration sensorimotrice chez les individus à HR. Delevoye-Turrell et al. (2012) ont étudié cette population lors d'une tâche de pointage manuel séquentiel, où les participants devaient pointer six cercles de manière rythmique avec leur doigt sur un écran tactile, et ceci à leur propre tempo, sans consigne de durée spécifique. Les résultats ont montré que les individus à HR avaient un rythme similaire à celui des neurotypiques, mais avec une variabilité temporelle plus importante. Bien que les auteurs n'aient pas observé de déficits sensorimoteurs flagrants, cette instabilité rythmique pourrait indiquer une fragilité dans l'intégration des informations sensorielles et motrices au fil du temps. La réalisation d'un rythme précis nécessite une coordination efficace des informations visuelles, tactiles, proprioceptives et motrices, et cette coordination pourrait être perturbée chez les individus à HR (Damme et al., 2021, 2024; Poletti et al., 2019; Poletti & Raballo, 2022).

Cette hypothèse d'une altération des processus sensorimoteurs chez les individus à HR semble être confirmée par des effets séquentiels observés sur les pentes relatives de décélération aux essais longs dans la tâche multidirectionnelle (étude 3). En effet, les individus à HR présentaient une décélération plus marquée en anticipation du signal cible au délai long, lorsque le délai précédent était long plutôt que court. Ces effets étaient inattendus pour deux raisons.

Premièrement, chaque essai impliquait une commande motrice différente. Dans nos autres données concernant les ralentissements anticipatoires (études 1 et 2), cette tâche empêchait l'utilisation des informations temporelles associées au mouvement précédent. Deuxièmement, au délai long, le délai précédent ne devrait pas influencer la préparation à l'arrêt dans l'essai actuel (étude 1 et 2), parce que la préparation à ce délai devrait être optimale quel que soit le modèle explicatif pour les effets séquentiels (Correa et al., 2006b; Los et al., 2014, 2017; Mento, 2017; Nobre et al., 2007; Salet et al., 2022; Vallesi et al., 2014; Vallesi & Shallice, 2007). Par conséquent, il était surprenant d'observer ces effets dans notre étude. Nous n'avions pas observé jusqu'ici d'effets séquentiels au délai long, et ceux-ci ne sont pas non plus observés dans la littérature, même chez l'enfant (Droit-Volet & Coull, 2016).

La présence d'un effet séquentiel dans cette condition chez les enfants à HR indique que leur préparation à l'arrêt est anormalement influencée par les informations des essais précédents. En considérant les théories basées sur l'évolution des probabilités d'occurrence de la cible, la persistance des effets séquentiels au délai long suggère que les enfants à HR n'ajustent pas leur prédiction en temps réel et ne tiennent pas compte de l'absence d'occurrence de la cible au délai court.

Ce pattern de résultats diffère considérablement de ceux observés chez les neurotypiques du même âge. En effet, des études ont montré que les enfants neurotypiques âgés de 8 à 12 ans réagissent plus fortement à la non-occurrence de la cible au délai court que les adultes (Mento & Vallesi, 2016). Cette réponse accentuée à la détection d'omission est suivie, chez les enfants, d'une augmentation de l'activité cérébrale dans les zones associées à la préparation temporelle. Cela suggère qu'en réaction à l'absence de la cible au délai court, les enfants neurotypiques actualisent automatiquement leurs prédictions et se préparent de manière significative à l'apparition de la cible au délai long. Ainsi, la

prédiction de l'occurrence de la cible au délai court est bien intégrée à la préparation motrice chez ces enfants (Debrabant et al., 2012; Mento & Granziol, 2020). Cette interprétation pourrait suggérer un déficit de prise en compte des probabilités d'apparition de la cible. Cependant les effets habituels d'amélioration des TRs aux délais longs, par rapport aux délais courts, semble contredire cette hypothèse, de même que l'absence d'effet séquentiels aux délais longs chez les individus à HR.

Pour ces raisons nous avons suggéré que chez les individus à HR, le problème réside dans l'intégration de la prédiction temporelle dans le programme moteur. Ce phénomène d'effets séquentiels au délai long n'est plus observé chez les individus à HR plus âgés. Ceci pourrait suggérer qu'en grandissant, la prédiction de l'occurrence du signal cible finit par s'intégrer à la commande motrice, comme c'est déjà le cas chez les enfants neurotypiques de tout âge (Edwards et al., 2019; Rasman et al., 2024; Wolpert et al., 1995). Ceci pourrait suggérer un défaut de l'optimisation motrice chez les individus à HR, cohérent avec la littérature qui suggère une amélioration progressive de l'efficacité motrice (Turrell et al., 2001).

7.4. La prédiction temporelle sensorimotrice chez les individus atteints de SZ

Étant donné que cette étude est toujours en cours, nos résultats sont préliminaires et notre échantillon est restreint. Nous n'avons donc pas encore pu analyser les indicateurs de la trajectoire chez les individus atteints de SZ. Nous nous sommes concentrés sur l'évaluation du bénéfice du passage du temps, qui a été démontré à plusieurs reprises comme étant altéré chez certains individus atteints de SZ (Foerster & Joos et al., 2024; Martin et al., 2017; Zahn et al., 1963). Nous avons examiné son impact sur les performances habituellement mesurées dans les tâches d'attente temporelle, telles que les TRs et les potentiels évoqués (CNV).

Dans le contexte des tâches d'attente temporelle, il est observé que plus l'intervalle entre la présentation du premier stimulus et celle de la cible est long, plus le niveau de préparation des participants augmente. Cela se traduit par des TRs plus rapides après un long délai par rapport à un délai court (Correa et al., 2006b; Mioni et al., 2018; Niemi & Näätänen, 1981; Vallesi & Shallice, 2007). Selon les théories basées sur l'évolution des

probabilités d'occurrence de la cible, cette différence de TR s'explique par le passage du temps, auquel est associé une augmentation croissante de la probabilité d'occurrence de la cible. Avoir un TR plus rapide au délai long qu'au délai court suggère que les participants sont capables de percevoir implicitement le passage du temps et d'actualiser leurs prédictions concernant l'occurrence de la cible en fonction de ce passage implicite du temps.

Des résultats récents indiquent que les individus atteints de SZ, et plus particulièrement ceux qui présentent des troubles du sens de soi, ne bénéficient pas du passage du temps de la même manière que les neurotypiques pour améliorer leurs performances (Foerster & Joos et al., 2024; Martin et al., 2017). En particulier, ils ne présentent pas de TRs plus rapides lorsque la cible apparaît après un délai long par rapport à un délai court.

Dans nos deux tâches motrices, nous avons observé un bénéfice du passage du temps sur les TRs similaire entre les individus atteints de SZ et les neurotypiques. Tous les participants, quel que soit leur groupe, réussissent à arrêter leur mouvement plus rapidement après un délai long qu'après un délai court.

Pour vérifier si ce bénéfice du passage du temps est préservé en raison de l'utilisation de tâches motrices, il sera essentiel d'examiner les performances des individus atteints de SZ dans notre tâche contrôle. Cette tâche, qui s'apparente aux protocoles d'attente temporelle de la littérature, nécessite que les participants restent immobiles entre la présentation du premier stimulus et l'occurrence du signal cible auquel ils doivent réagir en appuyant sur un bouton réponse. Actuellement, notre échantillon est trop petit pour observer une différence significative entre les TRs au délai long et ceux au délai court dans cette tâche, même chez les neurotypiques. Un échantillon plus important nous permettra de vérifier si nous reproduisons les altérations décrites dans la littérature concernant les TRs des individus atteints de SZ. Si tel est le cas, cela suggérera que bénéfice du passage du temps sur les TRs dans nos tâches motrices est liée à l'action.

Les résultats concernant la CNV pourraient déjà confirmer cette hypothèse et la dernière section de la discussion est consacré à ce potentiel évoqué.

7.5. La CNV

La CNV est un potentiel évoqué souvent altéré chez les individus atteints de SZ. En effet la CNV présente une amplitude moins négative dans cette population par rapport aux neurotypiques (Osborne et al., 2020). Dans notre première étude, nous avons établi la présence d'une CNV dans nos tâches motrices et montré que son amplitude était sensible aux capacités de prédiction temporelle. En effet, nous avons observé des effets séquentiels sur l'amplitude de la CNV : avant l'occurrence du signal cible au délai court, l'amplitude de la CNV était plus négative lorsque le délai de l'essai précédent était également court plutôt que long. Ces résultats reproduisaient ceux de la littérature, observés dans des tâches classiques d'attente temporelle (Los & Heslenfeld, 2005; Mento, 2017). Cependant, lors de l'étude 1, et contrairement aux effets séquentiels observés sur les résultats comportementaux, des effets séquentiels ont été constatés sur l'amplitude de la CNV, et ceci de manière indistincte dans nos deux tâches motrices. Cette observation nous a conduits à suggérer que les effets séquentiels sur cet indicateur reposent sur une prédiction temporelle indépendante du programme moteur exécuté.

Notre échantillon préliminaire de l'étude 4 (chez les individus atteints de SZ) ne nous a pas permis de vérifier pour l'instant la présence des effets séquentiels sur les amplitudes de la CNV chez nos participants. Cependant, à notre grande surprise, nous avons observé une restauration de l'amplitude de la CNV chez les individus atteints de SZ. Cette amplitude était comparable, voire plus négative, que celle des neurotypiques dans nos deux tâches motrices. En revanche, dans notre tâche contrôle, où les participants restaient immobiles entre le signal de départ et le signal cible, nous avons reproduit l'altération classique de la CNV chez les individus atteints de SZ, avec des amplitudes beaucoup moins négatives que celles des neurotypiques.

Bien que ces résultats doivent être interprétés avec prudence, ils suggèrent que l'exécution d'un mouvement pendant l'attente pourrait rendre le passage du temps plus concret pour les individus atteints de SZ. Nous proposons que cela est rendu possible par le flux d'informations sensorielles généré lors du mouvement : ce flux, qui informe le contrôle moteur de la progression du mouvement, pourrait rendre le passage du temps plus tangible. Toutefois, ces hypothèses demeurent spéculatives à ce stade.

Conclusion et Perspectives

Comme nous l'avons évoqué dans l'introduction, l'objectif principal de cette thèse a évolué au fil des études. Initialement, il s'agissait de développer un protocole basé sur une tâche d'attente temporelle intégrant des composantes motrices et tactiles, pour étudier les troubles cognitifs liés au sens de soi dans la SZ. Des découvertes inattendues dans les résultats de notre étude préliminaire ont finalement soulevé de nouvelles questions fondamentales. Nos travaux se sont alors orientés vers l'exploration des mécanismes de prédiction temporelle au cours de l'action motrice, aussi bien chez des populations neurotypiques que neuro-atypiques.

Dans le paradigme développé, les participants devaient initier un mouvement continu après un signal de départ, puis l'arrêter dès l'occurrence d'un signal cible. Ajouter cette composante motrice pendant l'attente nous a permis de recueillir des indicateurs cinématiques, reflétant l'anticipation de l'arrêt du mouvement. En plus de ces indicateurs, nous avons recueilli les mesures classiques des tâches d'attente temporelle, telles que les TRs et la CNV. Les effets séquentiels sur ces indicateurs ont été analysés afin d'évaluer l'influence de la prédiction temporelle sur la préparation et l'exécution de l'arrêt. Deux tâches ont été développées : l'une unidirectionnelle, où la trajectoire était la même à chaque essai, et l'autre multidirectionnelle, où la direction changeait d'un essai à l'autre. L'objectif était d'évaluer si la prédiction temporelle est intrinsèquement liée au mouvement exécuté ou si elle influence plus largement le système moteur. Il s'agissait également d'examiner comment cette prédiction évoluait selon les populations étudiées.

Les études 1 et 2 ont permis d'explorer les processus de prédiction temporelle associés à l'action motrice chez des individus neurotypiques, et d'examiner leur évolution au cours du neurodéveloppement typique. Les résultats de l'étude 1 ont révélé une dichotomie intéressante : les effets séquentiels observés sur les indicateurs comportementaux et EEG suggèrent l'existence de différents mécanismes de prédiction temporelle opérant à la même échelle temporelle. L'un de ces mécanismes est directement lié au mouvement et

se manifeste par des indicateurs comportementaux, tandis qu'un autre, moins dépendant du mouvement, est détecté à l'EEG. Ces résultats ont soulevé des questions sur l'interaction de ces processus et leur évolution durant le neurodéveloppement.

Les résultats de l'étude 2 ont permis de faire évoluer nos interprétations, en démontrant que les indicateurs comportementaux mesurés avant (pentes relatives de décélération) et après (TR) la réponse, révèlent des processus distincts, tous deux influencés par la préparation temporelle. Les pentes relatives de décélération montrent que la préparation motrice est présente dès l'âge de 9 ans, tandis que le TR indique une préparation sensorimotrice qui évolue tout au long de l'adolescence. Les différences de performance entre les groupes d'âge dans les tâches d'attente temporelle pourraient être attribuées à la maturation de ces processus sensorimoteurs.

Nos résultats obtenus chez les individus neurotypiques ont souligné l'importance de considérer plusieurs mécanismes de prédiction temporelle lors de l'élaboration de protocoles expérimentaux. Ils ont aussi soulevé des interrogations sur la préservation de ces mécanismes de prédiction temporelle chez les populations neuro-atypiques, connues pour des altérations des capacités de prédiction temporelle.

Les résultats de l'étude 3 montrent que les capacités de prédiction temporelle motrice semblent préservées chez les individus à HR de conversion psychotique. Cependant, ces individus rencontrent des difficultés à ajuster leurs prédictions aux régularités de la tâche, s'appuyant davantage sur leurs expériences récentes. En revanche, les résultats sur les TRs ont montré que les individus à HR conservaient une sensibilité aux probabilités d'occurrence de la cible. Pour cette raison nous avons suggéré que l'imprécision de la préparation motrice est plutôt liée à une intégration altérée de la prédiction sensorielle dans la planification du mouvement chez les individus à HR. Les stratégies de préparation motrice observées chez les individus à HR, différentes de celles des neurotypiques, pourraient viser à compenser une maturation sensorimotrice perturbée. Cela pourrait non seulement expliquer certains troubles du contrôle moteur dans cette population, mais aussi fournir des indices sur les déficits similaires observés chez les individus atteints de SZ, en lien avec le caractère neurodéveloppemental de ce trouble.

Les résultats préliminaires de l'étude 4 montrent que la réalisation d'un mouvement pendant l'attente pourrait permettre de restaurer le bénéfice du passage du temps sur les TRs et sur la CNV chez des individus atteints de SZ. La restauration de la CNV est une découverte inédite dans la SZ, et nous prévoyons d'étendre cette étude à un échantillon plus large afin de confirmer ces résultats. Si ce schéma se confirme, il pourrait enrichir notre compréhension des altérations de la prédiction temporelle et des déficits moteurs associés dans la SZ.

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ANNEXE

BRILL

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Temporal Order Judgments in Schizophrenia and Bipolar Disorders – Explicit and Implicit Measures

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Abstract

Ordering events in time is essential for the understanding of causal relationships between successive events. Incorrect causal links can lead to false beliefs and an altered perception of reality. These symptoms belong to psychosis, which is present in schizophrenia (SZ) spectrum and bipolar (BP) disorder. Experimental results show that patients with SZ have an altered perception of temporal order, while there are no data in patients with BP. We investigated the ability of patients with SZ, BP, and controls to judge the order of stimuli with a 100-ms Stimulus Onset Asynchrony (SOA), and how such large asynchronies facilitate temporal order judgments for small asynchronies. Explicit temporal order effects suggest that patients with SZ perform worse at a long SOA (100 ms) as compared to controls, whereas patients with BP show no difference compared to controls or to patients with SZ. Implicit order effects reveal improved performances in case of identical as compared to different relative order between two successive trials for all groups, with no differences between the groups. We replicated explicit order impairments in patients with SZ compared to controls, while implicit effects appear to be preserved. This difficulty for patients to consciously order stimuli in time might be understood under the light of the loosening-of-associations phenomenon well described in SZ. Further, we showed that patients with BP do not reveal such an explicit order impairment which is consistent with phenomenological descriptions, suggesting a difference in time experience in patients with SZ and BP.

Keywords

Temporal processing, temporal order, perception, psychosis

1. Introduction

"*I heard a scream followed by a car crash.*" – Sentence 1
"*I heard a car crash followed by a scream.*" – Sentence 2

In Sentence 1, the scream may have caused the accident. In Sentence 2, the accident may have caused the scream. The conclusions we draw from external events strongly depend on the order of those events. For example, Bedard and Barnett-Cowan (2016) have shown an impact of temporal order judgments on the interpretation of colliding figures as either bouncing or streaming. More generally, impaired temporal order judgments may affect our understanding of causal relationships of successive events. As a result of this, we may conclude incoherent interpretations from our surroundings, leading to an altered contact with the reality of the outer world. This is a key aspect of psychosis which can be manifested, for example, by delusions in patients (American Psychiatric Association, 2013). In the present study, we explore temporal order judgments in patients with schizophrenia spectrum disorder (SZ) and with bipolar disorders (BP).

Since the second half of the 20th century, psychiatric diagnoses have relied on the presence of several symptoms that are present for a certain period (American Psychiatric Association, 1952). Nevertheless, symptoms are usually not specific for a certain disease and can be shared between disorders. Some psychiatric disorders, like SZ and BP, can have psychotic, negative, and cognitive symptoms in common. These pathologies share even neurobiological and genetic risk factors (Yamada et al., 2020). In these cases, it may be difficult to make a diagnosis: around 30% of patients will have their diagnosis changed from BP to SZ (Chen et al., 1998). In order to provide better care for patients it is proposed to update current diagnostic tools (Hyman, 2007; Insel et al., 2010) since there is no reliable endophenotype or biomarker to distinguish BP and SZ.

The symptoms used to diagnose these two pathologies, and especially perceptual symptoms such as hallucinations, are quantified according to patients' subjective reports in clinical practice. Phenomenology has been used to deepen the understanding of the subjective reports of patients, i.e., their 'lived' experience. It is the study of the lived experience through phenomenology that highlighted the importance of the experience of time in psychosis. Both patients with SZ and patients with BP report a disturbed experience of time which could be related to an altered contact with reality (Fuchs, 2007; Gallagher, 2004; Minkowski, 2013; Moskalewicz & Schwartz, 2020; Uhlhaas & Mishara, 2007; Vogeley & Kupke, 2007). Interestingly, subjective reports suggest that the way the experience of time is disturbed in the two diseases differs. Specifically, what emanates from the reports of patients suffering from SZ, is a disturbed relationship to time that reflects the inability of patients to follow events in time in a continuous and

orderly way (Martin et al., 2014): "Time has disappeared. Not that it is longer or shorter, it's just not there; you could say there are bits of time, small pieces, shaken and mingled, or you could also say that there is no time at all" (quote in Spitzer, 1988, p. 167). For patients with BP in the manic phase, time has not disappeared but is limited to a permanent and timeless present: "It's like having this awareness, an almost physical sense of just having something that is not changing, that is just present. I mean it sounds maybe overly blunt to describe it as some sense of eternity, but that feels accurate. So, there is no past, there is no future, you are just in the nowness, and that's so terrifying because I think it's so rare as most of us aren't in that most of the time" (quote in Moskalewicz & Schwartz, 2020, p. 295). For patients with SZ, time is scrambled, which may result in a loss of contact with reality, while for patients with BP, the contact with reality is still present but altered (Minkowski, 2013). These phenomenological descriptions suggest that the way these two groups of patients process the structure of time is different. Whether the altered subjective experiences related to the structure of time, or their underlying mechanisms are a cause or a consequence of clinical symptoms is still an open question, and, in this work, we do not seek to take a stand in this question. Nonetheless, the experiences of time in patients with SZ and BP seem to be qualitatively different, which motivates our work to better elucidate potential underlying time processing deficits.

Experimentally, the processing of 'temporal structure' can be assessed using the simultaneity judgment (SJ) task and the temporal order judgment (TOJ) task (Thoenes & Oberfeld, 2017). In these tasks, we collect explicit behavioral measures, i.e., the participant's response to the explicit question asked on each trial: "were the two stimuli synchronous or asynchronous?" (in SJ tasks), or "which stimulus appeared first?" (in TOJ tasks). To the best of our knowledge there are no data on the processing of 'temporal structure' in patients with BP, while performance in visual TOJ and other sensory modalities in SJ tasks were found to be impaired in patients with SZ (Capa et al., 2014; De Boer-Schellekens et al., 2014; Giersch et al., 2009; Lalanne et al., 2012a, b; Stevenson et al., 2017), and these impairments increase with the level of schizotypy (Di Cosmo et al., 2021). In detail, the studies mentioned above show that patients with SZ require a longer delay between two successive visual stimuli (or Stimulus Onset Asynchrony, 'SOA') (1) to correctly judge them as asynchronous (as opposed to simultaneous) and (2) to correctly determine their order compared to healthy controls (HC). Moreover, previous results have shown that even when patients with SZ are able to perceive two stimuli as asynchronous, they have difficulties in judging which of the two appeared first (Capa et al., 2014). Being able to perceive two stimuli as asynchronous (SJ) and being able to tell which of the two came first (TOJ) are two different tasks, even though this is discussed in the literature (García-Pérez & Alcalá-Quintana, 2012; Vatakis et al., 2008). Asynchrony detection is a logical prerequisite for order perception, but TOJ may require additional mechanisms. The two-stage model of

Jaśkowski (1991) was applied to experimental TOJ data (Ulrich, 1987), and seems to support the hypothesis that SJ and TOJ tasks indeed involve different cognitive processes. Moreover, psychophysical studies comparing performances in the two tasks showed that participants' point of subjective simultaneity in SJ and TOJ tasks do not correlate, further suggesting that asynchrony and order detection rely on different processes (Love et al., 2013; Recio et al., 2019). Finally, EEG and fMRI correlates also support the idea that order processing requires an additional step to that of asynchrony processing (Basharat et al., 2018; Miyazaki et al., 2016; Binder, 2015).

As a matter of fact, in TOJ tasks participants have to choose between two possibilities: 'right stimulus appeared first' or 'left stimulus appeared first', on top of detecting that there is an asynchrony in both cases. The difficulties of patients with SZ to perceive which stimulus came first even when they can perceive that they are asynchronous could be based on a specific difficulty at consciously ordering stimuli and at making a decision about the order. Ordering implies comparing the onsets of two distinct stimuli, and may involve mechanisms that are closely related to consciousness (Gauthier et al., 2019; Grabot & van Wassenhove, 2017). The role of consciousness-related mechanisms is shown, e.g., in cases where the perceived order of events is reversed to match the perceived causality or sequence of events (Bechlivanidis et al., 2022; Capozzi et al., 2016; Geldard & Sherrick, 1972). Alternatively, patients with SZ may have difficulties already with the processing of a sequence of information (Giersch et al., 2016). In SJ tasks, healthy subjects have been shown to automatically plan for the perceptual processing of sequences of information, on the basis of previous trials (Marques-Carneiro et al., 2020): participants prepared to process stimuli in the same temporal order as in the previous trial. Such mechanisms imply a sequential processing of stimuli but do not necessitate an explicit comparison of stimulus onsets, or the formation of a conscious representation of order (Marques-Carneiro et al., 2020). We recently showed that not only asynchrony, but also temporal order may be processed at least partially implicitly (Chassignolle et al., 2021a). If patients with SZ are impaired at implicitly planning sequences or processing order, this might also explain their impairment in TOJ. In the current study, we use a TOJ task to test these two possibilities, since this task allows to analyze explicit as well as implicit effects. To test the possibility of an impairment at the implicit level, we used trial-to-trial effects.

Trial-to-trial effects are based on the principle that perceptual processing on a current trial (trial N) is influenced by information collected on a previous trial (trial $N-1$) (Recio et al., 2019; Roseboom, 2019). The response participants give on each trial is called 'explicit', because this measure is directly related to the instructions of the task. Conversely, trial-to-trial effects are considered 'implicit', since participants are not asked to judge what happened on the previous trial. In fact, the information from trial $N-1$ is not necessary to execute the task correctly

on a trial *N*. Nonetheless, information processed on trial *N* – 1 can alter the perception of trial *N* and thus also the respective responses given by the participants. Trial-to-trial effects can facilitate asynchrony/order detection and thus improve performance at shorter SOAs. For example, in a SJ task, the asynchrony between two stimuli (ordered right–left or left–right) is more easily detected on trial *N* if the order of stimulus onsets is the same as on trial *N* – 1, at least when the asynchrony on trial *N* – 1 is large enough (Marques-Carneiro et al., 2020). Similarly, in TOJ tasks, when the asynchrony on trial *N* – 1 is large and therefore the order is easily perceived, the perception of the order on trial *N* for small asynchronies (when perceptual evidence is weak) could be facilitated.

To investigate explicit and implicit measures of order discrimination in this study, we use a TOJ task (Sternberg & Knoll, 1973) with three different SOAs: 0 ms (synchrony, i.e., control condition), 17 ms (subthreshold asynchrony, i.e., condition of interest), and 100 ms (suprathreshold asynchrony, i.e., condition of interest) (Lalanne et al., 2012a). We aim to (1) replicate previous temporal order findings in patients with SZ, i.e., impaired performances in explicit measures (Capa et al., 2014; De Boer-Schellekens et al., 2014). As stated above, our explicit measure represents the mechanisms associated with consciousness, whereas our implicit measure represents the mechanisms that allow to optimize the processing of successive stimuli, without necessarily involving the explicit comparison of stimulus onsets. If patients with SZ benefit from trial-to-trial effects (implicit measures) but are still impaired at judging temporal order, it would suggest that they are mainly impaired in the mechanisms associated with conscious ordering. In order to examine the reverse hypothesis, i.e., altered mechanisms associated with the implicit processing of order, we have to examine implicit effects when explicit judgments are preserved. As a matter of fact, altered temporal order judgments might involve mechanisms associated with both implicit and explicit mechanisms. If patients with SZ have impaired trial-to-trial effects even when they correctly perceive the order on trial *N* – 1, then these results would suggest that the implicit mechanisms allowing them to prepare to process order are (also) impaired. Given the lack of basic knowledge in patients with BP, we aim to (2) investigate temporal order processing in these patients for the first time. Further, we aim to (3) compare temporal order processing between our two patient groups because of the differential subjective reports of time experiences between patients with SZ and BP (e.g., time is 'mingled' for patients with SZ whereas for patients with BP there is a permanent present, or 'nowness'). The phenomenological accounts of patients with BP of a feeling of permanent present are reminiscent of cognitive models that consider time processing via discrete temporal windows, or 'moments' (Pöppel, 1997; Stroud, 1956; Wittmann, 2011). In light of these models, extended temporal windows may explain patients' feelings of extended 'nowness', as if they were stuck in the present moment. However, the temporal scale of the windows which potentially relate to these altered 'now'

experiences (i.e., suprasecond scale) is not the same as the subsecond scale of the asynchronies used in the current study. Based on phenomenological reports, we may expect different patterns of results in the TOJ task between patients with SZ and BP, with either preserved performances in the TOJ task in patients with BP at the level of explicit measures and implicit measures, or different patterns of impairments at the two levels between the groups.

2. Material and Methods

2.1 Participants

Twenty four patients with SZ, 20 patients with BP and 31 HC were recruited for this study. All patients with SZ and BP were diagnosed according to the Diagnostic and Statistical Manual of Mental Disorders IV-TR (DSM-IV-TR, American Psychiatric Association, 2000) criteria. Patients did not suffer from neurological disorders or any other psychiatric disorder other than SZ or BP, respectively. They had to be free of psychoactive substances other than their treatment. Patients taking benzodiazepines were not included. Participants of the HC group did not suffer from any neurological disorders, nor did they have any history of psychiatric disease. None of the participants used cannabis in the last two months prior to the experiment, nor did they use any psychotropic substances for a duration equivalent to five half-lives of the drug. The visual acuity of all participants was tested with the Freiburg Visual Acuity Test (Bach, 1996). In case the test showed a visual acuity of less than 0.8, the participant could participate once her or his vision had been effectively corrected and verified. All participants gave their informed written consent, and the study was conducted in accordance with the Declaration of Helsinki. The project was approved by the regional ethics committee of the East of France (CPP EST IV).

In order to identify potential outliers in our participants we looked at performances in the condition with suprathreshold order. It is known, for HC, that an asynchrony of 100 ms is suprathreshold (Lalanne et al., 2012a). Thus, order should be easily perceivable with this SOA and we expected participants to perform close to 100% correct responses. Whether this high percentage of correct response rates was expectable for patients with SZ and BP was unclear. In order to still check for possible outliers (e.g., participants that did not understand the task or performed much worse than their group peers), we excluded all participant whose correct responses rate in the SOA = 100 ms condition was less than three standard deviations (SD) from the mean of the respective group. We detected one HC participant who had a correct response rate of only 46% (HC – mean: 94.63%, 3 * SD: 34.78). In order to check for a possible influence of our outlier criterion on the main results, we conducted the analysis with and without this participant

and found the same differences/similarities between the groups. Knowing this, we decided to exclude this participant in order to reduce uninformative variance within the HC group. For further analyses we used 30 HC. No outliers were detected in our two patient groups. Participants' demographic and clinical characteristics can be found in Table 1

During data acquisition, each patient (BP or SZ) was matched on age, sex, and education level with one HC participant. This resulted in two HC groups: one HC group matched to the SZ group and another HC group matched to the BP group. Due to difficulties in recruiting patients, equal sex representation across patient groups was unfortunately not possible.

Conducting statistical analyses using two HC groups leads to a decrease of statistical power along with a higher complexity of the analysis. To address this issue, we pooled our two HC groups into one HC group. We verified that the existence of differences/similarities between our groups on our measure of interest was not affected by this pooling of HC participants together. To do so, we compared results with either (a) two HC groups (one HC group for each patient group) or (b) one HC group (pooling all HC participants into one group). In detail, we performed four two-factor mixed analyses of variance (ANOVAs) that were identical regarding the dependent variable 'correct response rate' (i.e., 'right first' response when the stimuli's order of presentation was right–left and vice versa for 'left first' response) and regarding the within-factor 'SOA' (17 ms vs 100 ms). The separate ANOVAs differed in the composition of the between factor 'group': on the one hand, (a) we compared patients with SZ to their respective matched HC group and patients with BP to their respective HC group. On the other hand, (b) we compared each patient group to the pooled HC group. The ANOVAs showed the same group differences/similarities, irrespective of the HC group composition. This justifies using the pooled HC group in the following analyses.

To check whether our three groups significantly differ in age or in education level, we performed two one-factor ANOVAs with the between factor 'group'. The three groups: SZ, BP and HC, did not significantly differ in age ($F_{2,71} = 0.69$, $p > 0.05$, $\eta_p^2 = 0.02$). However, a significant difference between groups was found on their education level ($F_{2,71} = 12.98$, $p < 0.001$, $\eta_p^2 = 0.27$). According to Tukey HSD post hoc the SZ group had a lower mean education level (12.42 years) compared to the BP (15.70 years) ($p < 0.001$) and HC groups (14.37 years) ($p < 0.01$) while the education levels of patients with BP and the HC group did not significantly differ from each other ($p > 0.05$). The above presented analyses showed that we found the same differences/similarities between groups, regardless of whether we were comparing equivalent groups on education level (comparison between patients to their respective matched HC group) or not (comparison between patients to one pooled HC group). Thus, the factor education level cannot explain possible differences between groups in our results.

Table 1.
Participants' demographic and clinical characteristics

Groups	SZ	BP	HC
N	24	20	30
Gender (male/female)	20/4	5/15	15/15
Age (mean ± SD)	38.95 ± 9.88	37.55 ± 10.67	37.73 ± 9.96
Years of education (mean ± SD)	12.42 ± 2.30	15.70 ± 2.40	14.37 ± 1.94
Antipsychotic treatment (typical/atypical)	3/19	0/10	–
Treatment chlorpromazine equivalent mg/day (mean ± SD)	756.59 ± 1186.79	161.38 ± 106.43	–
Antiparkinsonian treatment (yes/no)	4/20	1/19	–
Anticonvulsant treatment (yes/no)	2/22	13/7	–
Antidepressant treatment (yes/no)	1/23	4/16	–
Anxiolytic treatment (yes/no)	1/23	0/20	–
Lithium (yes/no)	1/23	12/8	–
Disease duration in years (mean ± SD)	13.45 ± 9.77	8.25 ± 6.64	–
SANS total score* (mean ± SD)	38.89 ± 23.11	–	–
SAPS total score* (mean ± SD)	28.44 ± 24.32	–	–
QIDS–C16 total score (mean ± SD)	6.71 ± 5.27	4.10 ± 4.34	4,0 ± 3.31
YMRS total score (mean ± SD)	–	1.45 ± 2.56	–
CAPE total score (mean ± SD)	113.04 ± 36.13	139,10 ± 29.77	83.23 ± 24.18
fNART total score QI (mean ± SD)	106.02 ± 7.54	90.09 ± 13.12	110.73 ± 7.85

* Due to archival problems, SAPS was missing for 3 and SANS for 2 patients with SZ. Further, the fNART was not available for 5 patients with BP.
BP, bipolar disorders; CAPE = Community Assessment of Psychic Experiences (Stefanis et al., 2002); fNART = French National Adult Reading Test (Mackinnon & Mulligan, 2005); HC, healthy controls; QIDS-C16 = Quick Inventory of Depression Symptomatology-Clinician-Rated Version (Rush et al., 2003); SANS = Scale for Assessment of Negative Symptoms (Andreasen, 1989); SAPS = Scale for Assessment of Positive Symptoms (Andreasen, 1984); SD, standard deviation; SZ, schizophrenia; YMRS = Young Mania Rating Scale (Young et al., 2000).

Table 1 summarizes the scores of each group on the questionnaires mentioned below. All participants completed (1) the French National Adult Reading Test (fNART) which is used to give an indication of the premorbid cognitive abilities of participants (Mackinnon & Mulligan, 2005). It has to be noted that the fNART scores did not differ between patients with SZ and HC (Table 1). Patients with SZ must often stop their studies because of the early onset of the pathology, and the fNART could probably be a better way to match groups on their cognitive abilities than the education level. Further, participants also completed (2) the Community Assessment of Psychic Experience (CAPE) which is a questionnaire to assess whether participants have ever had psychotic-like experiences

(Stefanis et al., 2002), and (3) the 16-item Quick Inventory of Depressive Symptomatology Clinician rated (QUIDS-C16) which is used to assess depressive symptoms (Rush et al., 2003).

For patients with SZ we additionally completed the Scale for the Assessment of Positive Symptoms (SAPS) and the Scale for Assessment of Negative Symptoms (SANS) to assess positive and negative symptoms (Andreasen, 1984, 1989), respectively. For patients with BP, we additionally completed the Young Mania Rating Scale (YMRS) to assess manic symptoms in BP (Young et al., 2000). Importantly, patients with BP where euthymic, meaning they were in between acute phases (i.e., manic or depressive episode).

2.2 *Apparatus*

Participants were seated in a quiet room with dim lighting. Their chin was placed on a chin rest at a distance of 57 cm from a 21" Sony Triton CRT screen. The stimulation computer was a Hewlett-Packard Compaq 8100 Elite 2, and the task was programmed on MATLAB software (2007) by MathWorks (The MathWorks, Inc., Natick, MA, USA) using PsychToolbox (Brainard, 1997).

2.3 *Stimuli and Procedure*

The experimental paradigm is depicted in Fig. 1. The background was set to a black color throughout the experiment. After 3000 ms of this black background, a central fixation dot (diameter 0.3° VA) appeared, indicating the beginning of a trial. After a fixed period of 500 ms, two target squares (side length 2.5° VA)

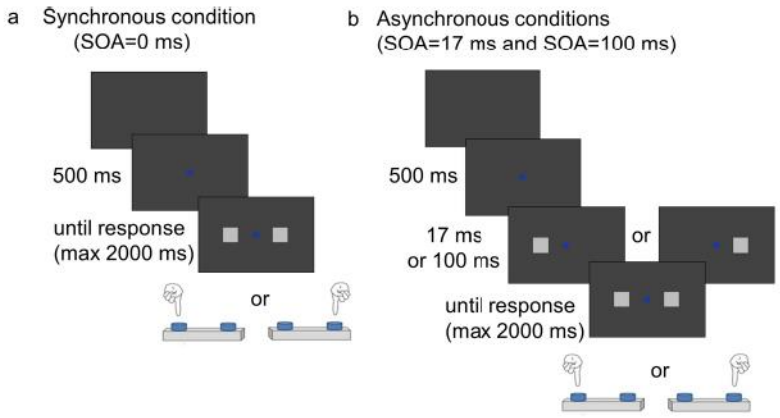

Figure 1. Procedure. A black screen with a central fixation dot indicated the beginning of a trial. After 500 ms, two squares appeared on both sides of the fixation dot, either (a) simultaneously [stimulus onset asynchrony (SOA) = 0 ms], or (b) asynchronously with either SOA = 17 ms or SOA = 100 ms. During asynchronous presentations, each order of appearance (left–right and right–left) was shown equally often (50% each). Participants' task was to determine the order of the two squares' appearance by responding to the side of the first target. Trials (SOA = 0 ms, SOA = 17 ms, SOA = 100 ms) were randomly presented throughout the experiment.

filled in grey appeared on both sides of the fixation dot. The distance between the centers of the two squares was set to 12.2° VA. The squares could either appear simultaneously on the screen, i.e., have an SOA of 0 ms, or they could appear asynchronously with a negative (i.e., left–right) or positive (i.e., right–left) SOA of 17 ms, or with a negative or positive SOA of 100 ms. If asynchronous, each order of appearance (i.e., left–right and right–left) was shown with equal probability, i.e., 50% each. The task consisted of a TOJ task in which participants were asked to determine the order of the two target squares' appearance and respond to the side of the first target via a left or right button press using the F and J keys on a standard keyboard. A total of 450 trials, i.e., 150 trials per SOA, were mixed and displayed in a randomized order. After the appearance of both squares, they stayed on the screen for a maximum of 2 s, or until a response press occurred.

2.4 Data Processing and Statistical Analysis

Data processing and analyses were carried out in R (RStudio Team, 2016). Trials corresponding to omission errors (i.e., no response given by the participant) and anticipatory responses (i.e., response time less than 150 ms) were discarded from further analyses.

Overall, the level of significance was set to $\alpha = 0.05$. All p values between 0.05 and 0.1 are considered as a tendency toward significance and will be mentioned as such in the text. Because the insignificant p values and the tendency p values are both greater than 0.05, nonsignificant p values will be simply reported as $p > 0.05$, while tendency p values will be reported by their exact values, e.g., $p = 0.069$. The partial eta-squared (η_p^2) values were added as a measure of effect size.

2.4.1 Explicit Measures — Asynchronous Conditions

To analyze explicit measures, i.e., the correct response rate, we first conducted a three-factor mixed ANOVA with the between factor 'group' (SZ vs BP vs HC) and the within factors 'SOA' (17 ms vs 100 ms) and 'order' (right–left vs left–right). Synchronous trials (SOA = 0 ms) were not considered since they cannot comprise order and were included only as a control condition (see subsection 2.4.2). We did not find a main effect of the within-factor 'order' on participants' correct response rate, nor did we find any interaction. Thus, in both asynchronous conditions, the correct response rate in all groups is not significantly influenced by the order of presentation of the stimuli. For the details of this analysis, see Supplementary Material S1. To simplify further analyses and to increase statistical power, we decided to average correct response rates across the order of presentation of the stimuli for each SOA and each group, separately. We label this averaged correct response rate as 'performance' (i.e., participants' performance at correctly detecting order, irrespective of the side of the first/second stimulus).

To analyze participants' performance in the main results, we conducted a two-factor mixed ANOVA with the between factor 'group' (SZ vs BP vs HC) and the

within-factor 'SOA' (17 ms vs 100 ms). Because the assumption of normal distribution was not respected in these datasets, we normalized them before applying the ANOVA. To do so, we used the 'ordernorm' function from the *bestnormalize* R package which allowed our datasets to follow a normal distribution (Peterson & Cavanaugh, 2020). To keep a normal distribution while preserving a mean and a standard deviation different from 0 and 1 respectively, we applied inverse z-scores to our datasets before conducting the statistical analysis.

A main effect of the between factor 'group' or an interaction would require subanalyses to localize differences. To do so, we compared groups two-by-two using two-factor mixed ANOVAs with the between factor 'group' (HC vs SZ, SZ vs BP, BP vs HC) and the within-factor 'SOA' (17 ms vs 100 ms). In this case, p values were corrected for multiple testing using the Bonferroni method.

2.4.2 Explicit Measures – Synchronous Condition

The synchronous condition (SOA = 0 ms) is a control condition allowing us to assess possible response biases for one side or the other. Although the squares appeared simultaneously at each trial, subjects had to respond with a left or right button press. Response biases could explain possible between-group differences in performance in the asynchronous trials. In order to check for this potential contributing factor, we performed a one-factor ANOVA with the between factor 'group' (SZ vs BP vs HC) on participants' rate of 'right first' response on 0 ms trials.

2.4.3 Implicit Measures – Influence of Suprathreshold Trial N – 1 (SOA = 100 ms) on Subthreshold Trial N (SOA = 17 ms)

We investigated the influence of the order of appearance of the stimuli on trial N – 1 on the processing of the order of appearance of the stimuli on the trial N, i.e., trial-to-trial effects or sequential dependency effects. Thus, we were interested in two scenarios: either the first stimulus appeared at the same side on trial N – 1 and on trial N (identical relative order), or it appeared at different sides on trial N – 1 and on trial N (different relative order). To investigate the influence of suprathreshold trial N – 1 on subthreshold trial N, we explored trial-to-trial effects for trial N – 1 with SOA = 100 ms on trial N with SOA = 17 ms. To do so, we performed a two-factor mixed ANOVA on participants' performance with the between factor 'group' (SZ vs BP vs HC) and the within-factor 'relative order' ('different' vs 'identical' between trials N – 1 and N). Importantly, for the suprathreshold order at 100 ms, one can differentiate between correct and false responses. Because the order of appearance at a SOA = 100 ms is rather easy to detect, errors did not occur often and the number of incorrect responses was not sufficient to perform separate analyses. We thus differentiated between only correct responses and all responses (correct + incorrect responses) on trial N – 1 and performed separate ANOVAs. Differentiating these two analyses allowed us to distinguish the

influence of trials $N-1$ with correct order detections from the influence of trials $N-1$ in general (comprising both correct and incorrect order detections).

2.4.4 Implicit Measures – Influence of Suprathreshold Trial N – 1 (SOA = 100 ms) on Synchronous Trial N (SOA = 0 ms)

One potential confounding factor that can influence participants' responses on a trial N with a subthreshold SOA is repeating the response given on trial $N-1$. Different rates of repeated responses between groups may result in between-group differences in performance for these trials. In order to exclude the possibility of different response repetition rates between our groups, we checked trial-to-trial effects of trial $N-1$ with SOA = 100 ms on trial N with SOA = 0 ms. We performed a two-factor mixed ANOVA with the between factor 'group' (SZ vs BP vs HC) and the within-factor 'order' (right–left vs left–right on trial $N-1$) on participants' rate of repeated responses on trial N (i.e., 'right first' response on trial N with SOA = 0 ms when response at trial $N-1$ was 'right first' and vice versa for 'left first' response).

2.4.5 Bayesian Analyses

In addition to the frequentist approach, we took a Bayesian approach to analyze the data. We had two main reasons for this choice: (1) the growing controversy in recent years against the meaning of the p value (Baker, 2016); (2) the capacity of the Bayesian approach to quantify the probability of H1 which goes beyond simple tests of H0 as performed with classical frequentist approaches (Dienes & Mclatchie, 2018). This is pertinent for the investigation of between-group differences/similarities, which is the aim of this work.

In the current study, we used non-informative priors for all analyses. We conducted multivariate Bayesian analyses on the same comparisons as previously described (subsections 2.4.1 – 2.4.4) in order to investigate within-factor effects. In case data were symmetrically distributed, we used a normal distribution to fit the data. In case the data were not symmetrically distributed, i.e., the explicit measures for asynchronous trials (subsection 2.4.1) and sensitivity measure in the psychometric function analysis (see Supplementary Material S2), we used a beta regression to fit the data.

In the results, e.g., $Pr(100\text{ ms} > 17\text{ ms})$ (i.e., probability that performance at a SOA = 100 ms is better than at a SOA = 17ms) denotes the probability of a difference for the respective comparison. For interactions, these probabilities are written as follows: $Pr(B > 0)$ with B being the coefficient of the interaction in the normal regression and $Pr(\text{OR} > 1)$ with OR $\exp^B$ being the coefficient of the interaction in the beta regression. We define meaningful effects with values that are $Pr > 0.95$ or $Pr < 0.05$ since both are equivalent, as $Pr\,(\text{A} > \text{B}) = 1 - Pr\,(\text{A} < \text{B})$.

All Bayesian analyses were conducted using the R packages *jags* (Plummer, 2003) and *brms* (Bürkner, 2021).

2.4.6 Correlation of Medication with Performance on Suprathreshold Trials (SOA = 100 ms)

To investigate the effect of medication on (1) the between-group difference and (2) on participants' performance, we conducted a Wilcoxon rank sum test to compare chlorpromazine equivalents between our two patient groups and Spearman correlation between participants' chlorpromazine equivalents and performance for the SOA = 100 ms condition.

3. Results

3.1 Explicit Measures — Asynchronous Conditions

Each group's performance for trials when stimuli were asynchronous, i.e., SOA = 100 ms and SOA = 17 ms, are depicted in Fig. 2a, b, respectively. At 100 ms, mean performances are 93.6% (± 8.6) for patients with BP, 96.3% (± 7.4) for HC, and 86.8% (± 15.9) for patients with SZ. At 17 ms, mean performances are 56.5% (± 7.0) for patients with BP, 56.5% (± 5.8) for HC, and 53.2% (± 5.2) for patients with SZ.

The two-factor mixed ANOVA on participants' performance revealed a significant main effect of between factor 'group' (SZ vs BP vs HC) ($F_{2,71} = 5.52$, $p < 0.01$, $\eta_p^2 = 0.14$) and a significant main effect of within-factor 'SOA' (17 ms vs 100 ms) ($F_{2,71} = 1037.84$, $p < 0.001$, $\eta_p^2 = 0.94$). Globally, participants performed significantly better in trials with SOA = 100 ms (92.5%) as compared to trials with SOA = 17 ms (55.4%). A tendency for a significant interaction between factors was found ($F_{2,71} = 2.60$, $p = 0.081$, $\eta_p^2 = 0.07$).

The sub-analysis with a two-factor mixed ANOVA on participants' performance for the comparison between HC vs patients with SZ revealed a significant main effect of between factor 'group' ($F_{1,52} = 9.89$, $p < 0.01$, $\eta_p^2 = 0.16$). Patients with SZ performed significantly worse (70%) than HC (76.4%). Further, we found significantly worse performance at SOA = 17 ms as compared to SOA = 100 ms ($F_{1,52} = 645.04$, $p < 0.001$, $\eta_p^2 = 0.93$). A tendency for a significant interaction between factors was found ($F_{1,52} = 4.40$, $p = 0.082$, $\eta_p^2 = 0.08$).

The sub-analysis with a two-factor mixed ANOVA on participants' performance for the comparison between SZ vs BP revealed no significant main effect of between factor 'group' ($F_{1,42} = 4.04$, $p > 0.05$, $\eta_p^2 = 0.09$). Patients with BP did not perform significantly differently (75%) from patients with SZ (70%). Further, we found significantly worse performance at SOA = 17 ms as compared to SOA = 100 ms ($F_{1,42} = 423.34$, $p < 0.001$, $\eta_p^2 = 0.91$). No significant interaction between factors was found ($F_{1,42} = 0.97$, $p > 0.05$, $\eta_p^2 = 0.02$).

The sub-analysis with a two-factor mixed ANOVA on participants' performance for the comparison between HC vs BP revealed no significant main effect of between factor 'group' ($F_{1,48} = 0.64$, $p > 0.05$, $\eta_p^2 = 0.01$). Patients with BP did

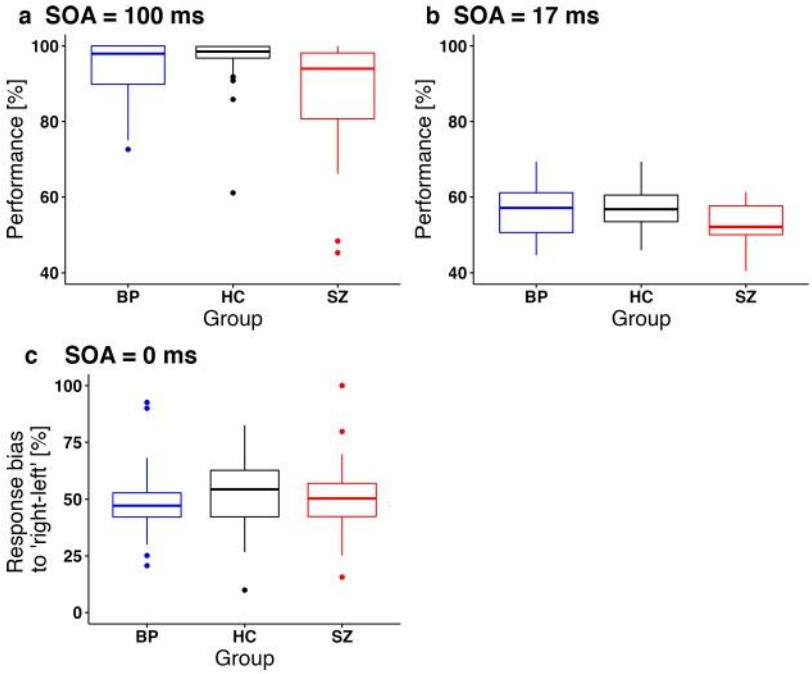

Figure 2. Performance on trial *N* shown using boxplots with quartiles [values represent mean ± standard deviation (SD)]. In panels a [stimulus onset asynchrony (SOA) = 100 ms] and b (SOA = 17 ms), performance in the temporal order judgment (TOJ) task is depicted in percentage correct responses. In panel c (SOA = 0 ms), stimuli were presented simultaneous and thus no correct response can be determined. Instead, the response bias towards answering 'right first' is depicted. The data are shown for patients with bipolar disorder (BP) in blue, for healthy controls (HC) in black, and for patients with schizophrenia (SZ) in red. Dots represent individual data points out of the quartile interval.

not perform significantly differently (75%) from HC (76.4%). Further, we found significantly worse performance at SOA = 17 ms as compared to SOA = 100 ms ($F_{1,48} = 1579.69$, $p < 0.001$, $\eta_p^2 = 0.97$). No significant interaction between factors was found ($F_{1,48} = 1.91$, $p > 0.05$, $\eta_p^2 = 0.04$).

The multivariate Bayesian analysis of the factor group showed no meaningful difference between HC and patients with BP ($Pr = 0.47$), or between patients with SZ and patients with BP ($Pr = 0.86$), while patients with SZ showed lower performances than HC, but the difference was only marginal ($Pr = 0.90$). Further, there was a clearly meaningful effect for SOA with a better performance at 100 ms as compared to 17 ms [OR = 33.6, CI95%: 21.4–49.4, $Pr(100\text{ ms} > 17\text{ ms}) > 0.99$]. We first took into account patients with SZ and HC and found a meaningful interaction effect ($Pr = 0.01$), reflecting a larger group difference for 100 ms (advantage of

9.5% for HC compared to SZ) than for 17 ms (advantage of 3.3% for HC compared to SZ). We then took into account patients with SZ and patients with BP and found a marginal interaction effect ($Pr = 0.93$), suggesting similar trends as the previous analysis, with BP performance being close to HC. No meaningful interaction effect was found in the analysis with patients with BP and HC ($Pr = 0.27$).

3.2 Explicit Measures — Synchronous Condition

We investigated whether our three groups showed differences in response biases, i.e., a tendency to press on the left or on the right button when stimuli were synchronous, by looking at participants' 'right first' response rate on synchronous trials (SOA = 0 ms) (Fig. 2c). At 0 ms, mean 'right first' response rate was 49.9% (± 18.2) for patients with BP, 51.3% (± 16.1) for HC, and 50.9% (± 17.7) for patients with SZ.

We performed a one-factor ANOVA on participants' 'right first' response rate which showed no significant main effect of the between factor 'group' ($F_{2,72} = 0.04$, $p > 0.05$, $\eta_p^2 = 0.001$) (Fig. 2c). In line with this, we found no meaningful effect of group in the multivariate Bayesian analyses (all *Pr* between 0.31 and 0.42).

3.3 Implicit Measures — Influence of Suprathreshold Trial N – 1 (SOA = 100 ms) on Subthreshold Trial N (SOA = 17 ms)

3.3.1 Only Correct Order Detection on Trial N – 1

We investigated the effect of trial $N - 1$ with SOA = 100 ms on performance on trial N with SOA = 17 ms to isolate markers of predominantly implicit mechanisms associated with ordering. Each group's performance for trial N (SOA = 17 ms) preceded by trial $N - 1$ (SOA = 100 ms) where only correct detections of order occurred are depicted in Fig. 3a. At trial N, mean performances were 58.4% (± 21.5) for patients with BP, 57.9% (± 19.1) for HC and 55.7% (± 16.2) for patients with SZ.

A two-factor mixed ANOVA on participants' performance at trial N revealed no significant main effect of between factor 'group' (SZ vs BP vs HC) ($F_{2,71} = 0.65$, $p > 0.05$, $\eta_p^2 = 0.02$) but a significant main effect of within-factor 'relative order' (different vs identical between trials $N - 1$ and N) ($F_{1,71} = 41.03$, $p < 0.001$, $\eta_p^2 = 0.37$) (Fig. 3a). Participants performed significantly better on trial N when the relative order was identical (67.3%) as compared to different (47.3%) on trial $N - 1$. No interaction between factors was found ($F_{2,71} = 0.98$, $p > 0.05$, $\eta_p^2 = 0.03$).

Similarly, the multivariate Bayesian analyses showed no meaningful effect of group (all *Pr* between 0.27 and 0.54) and a clearly better performance for identical as compared to different relative order between trials $N - 1$ and N [OR = 1.2, CI95%: 1.13–1.29, $Pr(ID > DIF) = 0.99$]. We explored the interaction between the group and the advantage provided by identical vs different relative order trials. We did not find meaningful interaction effects between patients with SZ and HC

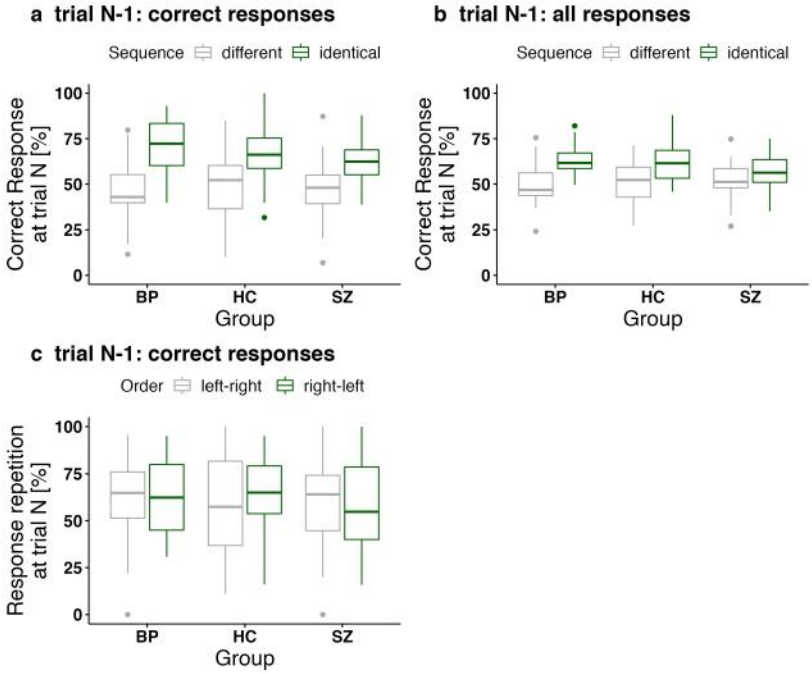

Figure 3. Percentage of correct responses at trial *N* (SOA = 17 ms) (a, b), or percentage of repeated responses at trial *N* (SOA = 0 ms) (c) in dependence of trial *N* – 1 (SOA = 100 ms) using boxplots with quartiles [values represent mean ± standard deviation (SD)]. When trial *N* was asynchronous (a, b), trial *N* – 1 and trial *N* could either have the first stimulus appear on the same side ('identical', green boxplots) or on different sides ('different', grey boxplots). Panel a depicts this when considering only correct responses at trial *N* – 1, and panel b depicts this when considering all responses (correct + incorrect responses) at trial *N* – 1. Panel c depicts the rate of repeated responses on trial *N* (SOA = 0 ms) depending on the order in trial *N* – 1 ('left–right' in grey, 'right–left' in green) and considering only correct responses on trial *N* – 1 (SOA = 100 ms). Data are shown for patients with bipolar disorder (BP), for healthy controls (HC), and for patients with schizophrenia spectrum (SZ). Dots represent individual data points out of the quartile interval.

(*Pr* = 0.30), nor between patients with BP and HC (*Pr* = 0.88). We did find a less pronounced advantage in patients with SZ as compared to patients with BP, but the interaction only approached our relevance criterion (*Pr* = 0.945).

3.3.2 All Responses (Correct + Incorrect Order Detection) on Trial N – 1

After the analysis of trials following a correct response, we analyzed implicit effects by taking all *N* – 1 trials into account. Each group's performance for trial *N* (SOA = 17 ms) preceded by trial *N* – 1 (SOA = 100 ms) where all responses (correct + incorrect responses) were considered are depicted in Fig. 3b. At trial *N*, mean performances were 57.1% (± 12.9) for patients with BP, 57.1% (± 12.7) for HC, and 53.8% (± 10.2) for patients with SZ.

A two-factor mixed ANOVA on participants' performance at trial *N* revealed no significant main effect of between factor 'group' ($F_{2,71} = 1.71, p > 0.05, \eta_p^2 = 0.05$) but a significant main effect of within-factor 'relative order' between trials *N* – 1 and *N* ($F_{1,71} = 26.71, p < 0.01, \eta_p^2 = 0.27$) (Fig. 3b). Participants performed significantly better at trial *N* when the relative order was identical (61%) as compared to different (51.1%) at trial N – 1. No interaction was found ($F_{2,71} = 1.41, p > 0.05, \eta_p^2 = 0.04$).

Similarly, the multivariate Bayesian analysis showed no meaningful effect of group (all *Pr* between 0.39 and 0.45) and clearly better performances for identical as compared to different relative-order trials [OR = 1.12, CI95%: 1.07–1.17, *Pr*(ID > DIF) = 0.99]. As depicted in Fig. 3b, the advantage provided by identical vs different relative-order trials is more pronounced in patients with BP. This is confirmed by a meaningful interaction effect between patients with SZ and patients with BP (*Pr* = 0.96), but there is no meaningful interaction effect between patients with BP and HC (*Pr* = 0.69). We found a marginal interaction effect between patients with SZ and HC (*Pr* = 0.08).

3.4 Implicit Measures — Influence of Suprathreshold Trial N – 1 (SOA = 100 ms) on Synchronous Trial N (SOA = 0 ms)

We investigated whether our three groups showed differences in response repetition from trial *N* – 1 with SOA = 100 ms on trial *N* with SOA = 0 ms by looking at participants' response repetition rate on trial *N* (i.e., 'right first' response on trial *N* with SOA = 0 ms when response at trial *N* – 1 was 'right first' and vice versa for 'left first' response) (Fig. 3c). At trial *N*, mean response repetition rate from asynchronous trial *N* – 1 to synchronous trial *N* were 61.1% (± 21.3) for patients with BP, 61.1% (± 23.3) for HC, and 58.1% (± 24.1) for patients with SZ.

The two-factor mixed ANOVA on participants' response repetition rate from trial *N* – 1 on trial *N* revealed no significant main effect of between factor 'group' (SZ vs BP vs HC) ($F_{1,71} = 0.33, p > 0.05, \eta_p^2 = 0.01$) or main effect of within-factor 'order' (right–left vs left–right on trial *N* – 1) ($F_{1,71} = 0.20, p > 0.05, \eta_p^2 = 0.003$) (Fig. 3c). No significant interaction was found ($F_{1,71} = 0.44, p > 0.05, \eta_p^2 = 0.01$). In line with these results, the multivariate Bayesian analysis showed no meaningful effects (all *Pr* between 0.15 and 0.88).

3.5 Correlation of Medication with Performance on Suprathreshold Trials (SOA = 100 ms)

We found a significant difference in the chlorpromazine equivalent doses between SZ and BP [$W = 195.5, p < 0.05$]. However, the explicit measure performance at 100 ms did not significantly correlate with the chlorpromazine equivalent doses for patients with SZ ($r_{18} = -0.06, p > 0.05$), nor for patients with BP ($r_{11} = -0.1, p > 0.05$).

4. Discussion

The main aim of this study was to provide experimental data on how patients with SZ and patients with BP process time. To answer this question, we used a TOJ task where participants had to order two asynchronous stimuli in time and we measured order processing by means of explicit and implicit measures, i.e., trial-to-trial effects.

For our explicit measures, frequentists analyses (i.e., ANOVAs) revealed a significant group difference in TOJ performance, but only a tendency for a significant interaction between factors group and SOA. Sub-analyses showed that this group difference came from lower TOJ performance in patients with SZ compared to HC. Frequentist sub-analyses failed to reveal whether these altered performances are present only for supra- (100 ms) or sub- (17 ms) threshold asynchronies. Complementing these frequentist analyses with Bayesian analyses confirmed the TOJ impairment in patients with SZ relative to HC and pointed to a larger impairment for SOA = 100 ms trials compared to SOA = 17 ms trials. The results further indicated a possible difference between patients with SZ and patients with BP (probability of 93%). Such differences could not be explained by different response biases. When the SOA was 0 ms on trial *N*, i.e., when the stimuli appeared synchronously, there was no right or left response bias in any of the groups. One might hypothesize that alterations in explicit measures found in patients with SZ may originate from lower levels of education compared to HC rather than altered mechanisms related to conscious ordering. However, this possibility was excluded in our study, since we verified that the results were the same when comparing patients with SZ to a subgroup of HC that were matched on level of education. In addition, the same fNART scores in patients with SZ and in HC point toward similar premorbid cognitive abilities in those two groups. As for patients with BP, all types of analyses indicated similar TOJ performance between HC and patients with BP.

Our results are interesting from several standpoints. First, they support our hypothesis concerning the performance of patients with SZ on an explicit level, in line with the literature showing that patients with SZ have difficulties in processing order on a temporal scale that is suprathreshold for detecting asynchronies (Capa et al., 2014). This is also in line with the results on participants' order discrimination sensitivity based on psychometric curve fitting (the small number of SOAs is a limitation and the results are reported in Supplementary Material S2). Patients with SZ had lower order discrimination sensitivity compared to HC according to frequentist analyses and compared to both HC and patients with BP according to Bayesian analyses. Second, our results indicate that the performance of patients with BP at ordering events in time, as measured in our task, is not different from HC's. To the best of our knowledge, our experiment provides, for the first time, empirical data on the processing of 'temporal structure' (Thoenes & Oberfeld,

2017) in BP disorder. There seems to be a difference between patients with BP and SZ in their temporal order processing abilities of supra- and subthreshold asynchronies, as assessed with our explicit measure. Patients with BP, like patients with SZ, have already shown temporal impairments in the estimation of subsecond durations (Bolbecker et al., 2014). However, duration refers to the content of time, whereas temporal order concerns time structure. Phenomenologists make a difference between patients with BP and SZ mainly on time structure, which can explain that we did not find impairments in patients with BP in the TOJ task. Our finding parallels the qualitatively different phenomenological accounts of time experiences in the two disorders and highlights the value of phenomenology to complement clinical research. It should be noted that our sample sizes are small and the abovementioned group differences/similarities need to be confirmed in larger groups.

For our implicit measures, we were interested in sequences of SOAs where a trial $N-1$ with SOA = 100 ms preceded a trial N with SOA = 17 ms. These trial-to-trial effects were chosen because they are proposed to reflect perceptual processes that are less influenced by mechanisms associated with conscious ordering, as compared to explicit responses given on a trial N. As expected (Marques-Carneiro et al., 2020), all analyses showed better performance when the successive asynchronies were displayed with stimuli shown in identical rather than different relative order. Here, when considering only correct responses on trial $N-1$, i.e., when participants correctly identified the suprathreshold order on the previous trial, neither frequentist analyses nor Bayesian analyses revealed a difference in trial-to-trial effects between groups. Furthermore, the relative order had similar effects in all groups, which allows us to discard an explanation in terms of response repetition. If patients had mainly repeated their responses, and more so than controls, then we should have seen impaired performance in patients when the order changed from one trial to the other. This was not the case. Also, when the SOA was 0 ms on trial N, i.e., when the stimuli were displayed synchronously, the rate of response repetition was similar across groups. In all, the significant group differences in explicit measures and the preserved trial-to-trial effects in patients with SZ suggest that patients' impairments at order detection are related to difficulties in mechanisms associated with conscious ordering rather than at an implicit perceptual processing level.

Interestingly, when considering all responses (correct + incorrect order detection) on trial $N-1$, Bayesian analyses (but not ANOVAs) showed that the advantage provided by identical vs different relative order is less pronounced in patients with SZ as it is in HC and BP groups. This suggests that when patients with SZ identify incorrectly the order of a 100 ms asynchrony, then they do not benefit from an order similarity on the subsequent 17 ms trial, i.e., their order detection performance is not facilitated. One possible explanation of this alteration in patients with SZ could be found in an erroneous response repetition: if participants repeat

their response on trial N after an error on trial $N-1$, then it will result in an error for identical relative-order trials. However, we did not find any group difference regarding response repetitions and thus this cannot explain the altered trial-to-trial effects in patients with SZ. Our results rather suggest that when patients make an error in the TOJ task, their explicit processing of order is truly altered, leading to a reduction of advantage for identical order trials after an error. In contrast the advantage is preserved in case of a correct response, thus enabling a preserved facilitation of order processing on the next trial. Understanding this effect on trial-to-trial effects would require analyzing sequences with only incorrect responses on trial $N-1$. This was unfortunately not possible with our current dataset since the number of such sequences was too low (on average 3.5 trials per group). Further studies focusing specifically on incorrect responses in trial-to-trial effects are needed to clarify our findings on implicit measures.

A recurrent question in patient studies is the impact of psychotropic drugs. The chlorpromazine equivalent doses differed between the two patient groups but did not correlate with the performance of our participants. Moreover, in the Bayesian analyses on explicit and implicit measures (when considering only correct responses on trial $N-1$) differences were observed in the SZ group compared to HC and BP groups. HC and patients with BP performed similarly on both types of measures, while approximately half of patients with BP were under antipsychotic medication. These results are consistent with recent data in healthy volunteers, which showed that a depletion in dopamine precursors affects duration perception but not temporal order processing (Chassignolle et al., 2021b). The difficulty of patients with SZ in processing temporal order is thus unlikely to be related to their treatment. The main limitation of this study is the relatively small sample size of the patient groups. Consequently, it was not feasible to correlate symptom severity of the patients with their performance.

In all, our study brings further evidence of a deficit in temporal order processing in SZ. The origin of this impairment is proposed to be at the level of mechanisms associated with conscious ordering, as suggested by altered ordering performances in explicit measures, but a relative preservation of the trial-to-trial effects in patients with SZ. These patients benefit in the same way as HC from a suprathreshold asynchrony presented on the previous trial (at least when the order on the previous trial was identified correctly), while they showed impaired performances in explicit measures compared to both HC and BP groups. Our study also yields empirical evidence of preserved temporal order processing abilities in patients with BP who perform similarly to HC, at least for the range of asynchronies used in our task. The difference in temporal order processing between patients with SZ and BP fits with the qualitatively different phenomenological accounts related to time in the two disorders. Further studies in this domain, and specifically those inspired by phenomenological accounts, may improve the differentiation of patients with BP and patients with SZ.

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Supplementary Material

Supplementary material is available online at:
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Alana ARROUET

Exploration de la Prédiction Temporelle associée à la Motricité chez les Individus Neurotypiques et Neuro-atypiques

L'objectif de la thèse était d'explorer l'impact de la prédiction temporelle sur la planification et l'exécution de mouvements. Nous avons utilisé des tâches où les participants arrêtaient un mouvement de l'index en réponse à un signal prédictible et étudié comment cette prédiction influençait la préparation et l'exécution de l'arrêt. Chez les neurotypiques, nos résultats ont révélé plusieurs prédictions temporelles opérant simultanément : une prédiction liée à la commande motrice influençant la préparation, une prédiction sensorimotrice affectant l'exécution et une prédiction indépendante de la commande motrice reflétant une attente cognitive. La prédiction temporelle sensorimotrice évolue avec le développement et semble altérée chez les individus à haut risque génétique de conversion psychotique. Chez les individus atteints de schizophrénie, des résultats préliminaires suggèrent que la réalisation d'un mouvement pourrait rétablir les capacités de prédiction temporelle. Cette thèse apporte des connaissances sur l'intégration des prédictions temporelles au programme moteur et questionne les mécanismes de l'intégration sensorimotrice.

Mots-clés : Prédiction Temporelle ; Effets Séquentiels ; Motricité ; Haut-Risque Génétique de Conversion Psychotique ; Schizophrénie

The aim of this thesis was to explore the impact of temporal prediction on movement planning and execution. We used motor tasks in which participants stopped an index finger movement in response to a predictable target signal and examined how this prediction influenced both movement preparation and stopping execution. In neurotypical individuals, our findings revealed multiple temporal prediction mechanisms operating simultaneously: one linked to motor commands affecting preparation, a sensorimotor prediction influencing execution, and an independent prediction reflecting cognitive anticipation. Sensorimotor temporal prediction evolves with development and appears to be impaired in individuals at high genetic risk of psychotic conversion. In people with schizophrenia, preliminary findings suggest that performing a movement may help restore temporal prediction abilities. This thesis provides insights into how temporal predictions are integrated into motor programs and raises questions about the mechanisms underlying sensorimotor integration.

Keywords: Temporal Prediction; Sequential Effects; Motor System; High Genetic Risk of Psychotic Conversion; Schizophrenia