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Contribution des doigts au développement des compétences numériques et arithmétiques typique et atypique

Thèse présentée en vue de l'obtention d'un doctorat en Sciences Psychologiques et de l'Éducation

par

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Résumé

Alors que l'utilisation des doigts par les enfants fait encore l'objet de débats chez les enseignants et les scientifiques, la présente thèse a été conduite afin de mieux comprendre *la contribution des doigts dans le développement des compétences numériques et arithmétiques typique et atypique*. L'étude des habiletés sensori-motrices (gnosies digitales et habiletés motrices fines (HMF)) était au cœur de ce projet de thèse. Après avoir examiné la littérature à travers deux revues narratives et une revue méthodique, quatre recherches expérimentales ont été conduites. Les deux premiers travaux, menés chez des enfants tout-venant âgés de 3 à 8 ans, visaient *à clarifier le rôle des habiletés sensorimotrices dans le développement des compétences arithmétiques ainsi que les processus sous-jacents à ces relations.* Entre 3 et 5 ans, nos recherches ont montré que les HMF étaient un meilleur prédicteur des habiletés arithmétiques que les gnosies digitales. Par ailleurs, les HMF sont liées aux compétences arithmétiques par la maitrise des concepts cardinaux. A partir de 6 ans, ce pattern de résultats change puisque que seules les gnosies digitales apparaissent comme étant un prédicteur significatif du développement arithmétique. Cette relation n'est pas médiée par l'utilisation du comptage sur les doigts. Conduites auprès d'enfants présentant un déficit moteur (TDC et IMC), les deux dernières recherches *visaient à explorer les conséquences de ces altérations motrices sur les traitements numériques et à proposer des pistes d'intervention*. Alors qu'ils présentent des HMF déficitaires, les enfants TDC produisent des gestes de comptage semblables à ceux d'enfants tout-venant. Ils sont davantage limités par leurs ressources en mémoire de travail que par leur déficit moteur pour traiter des tâches ordinales sollicitant fortement la mémoire de travail. Ce n'est que quand le déficit moteur est très important, que le recours aux supports externes (doigts et matériel de manipulation) semble fortement affecté. C'est le cas chez NG, un enfant IMC dont le handicap moteur empêche l'utilisation de ces supports pour soulager sa mémoire de travail déficitaire, lors des traitements arithmétiques. Une rééducation du calcul, ancrée dans l'Evidence Based Practice (EBP) et conçue à partir d'un matériel adapté a été conduite avec succès auprès de cet enfant. La présente thèse ouvre de nombreuses perspectives pour la conduite de futures recherches à visée tant fondamentale que clinique.

Abstract

While the use of fingers by children is still a matter of debate among teachers and scientists, our thesis was conducted to *better understand the contribution of fingers in the development of typical and atypical numerical and arithmetic skills*. This thesis project primarily focused on examining sensorimotor finger skills (i.e., finger gnosia and fine motor skills (FMS)). After examining the literature through two narrative reviews and a scoping review, four experimental investigations were conducted. The first two studies, conducted with typically developed children aged 3 to 8, aimed to clarify the role of sensorimotor finger skills in the development of arithmetic, and the processes underlying this relationship. Between the ages of 3 and 5, our research showed that FMS was a better predictor of arithmetic skills than finger gnosia. FMS are related to arithmetic skills through cardinal knowledge. From age 6, this pattern of results changes, as only finger gnosia appear to be a significant predictor of arithmetic development. This relationship is not mediated by the use of finger counting. The other two studies, carried out on children with fine motor disorders (Developmental Coordination Disorder (DCD) and Cerebral Palsy (CP)), aimed to explore how these impairments affect numerical processing, and to suggest avenues of intervention. Children with DCD were less accurate than theirs typically developing peers in using finger counting to solve numerical problem with high working memory load. This group difference could not be accounted by poor finger counting skills as finger counting movement turned out to be as functional in children with DCD as in their peers. The use of external supports (such as fingers and manipulatives) appears to be significantly impacted only in cases of severe motor deficits. This was the case with NG, a child with CP, whose motor disability prevented him from using these supports to alleviate his working memory deficits, during arithmetic processing. In accordance with evidence-based practice in psychology, an arithmetical program was successfully implemented with NG. This thesis opens up large avenues for future fundamental and clinical researches.

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Overview

Partout dans le monde, les doigts sont utilisés pour traiter des problèmes numériques. Ces habitudes, ancrées dans des pratiques culturelles (Bender & Beller, 2012; Lindemann et al., 2011), sont couramment observées chez les individus, du plus jeune âge à l'âge adulte (Fischer, 2008; Hohol et al., 2018). Apprise au gré des interactions avec les pairs ou par des apprentissages scolaires plus formels, l'utilisation des doigts soutient particulièrement l'acquisition des compétences numériques et des habiletés arithmétiques des jeunes enfants. Dans les milieux scolaires, le recours à cette pratique n'est pas toujours bien accepté par les enseignants qui peuvent ainsi la déconseiller voire l'interdire auprès de leurs élèves (Boaler & Chan, 2017, 2018; Multu et al., 2020) pour favoriser des approches centrées sur des apprentissages plus abstraits tels que le calcul mental. Pourtant, les recherches menées dans le domaine de la psychologie cognitive au cours de ces dernières décennies ont largement montré un apport bénéfique de cette pratique sur le développement numérique de l'enfant.

Dans leur modèle développemental, Roesch et Moeller (2015) ont rassemblé un ensemble de preuves qui ont permis de clarifier la contribution des doigts à différents niveaux du développement numérique. Ils ont ainsi mis en évidence que les doigts étaient utilisés par les enfants pour exécuter des *gestes de comptage* (i.e., lever les doigts l'un après l'autre ; *Finger counting* dans la littérature anglophone) ou des *gestes numériques* (i.e., gestes ayant une valeur cardinale; *Finger gesture* dans la littérature anglophone ; e.g., pouce, index et majeur levés simultanément pour représenter "trois") qui les aideraient non seulement à visualiser et à combiner les quantités traitées dans un problème mais qui supporteraient également l'acquisition des compétences numériques précoces. Pour que ces gestes soient fonctionnels, l'enfant doit recourir aux habiletés sensori-motrices (HSM) nécessaires au contrôle et à la coordination des mouvements des doigts et de la main. Ce n'est que depuis une quinzaine d'années que les auteurs ont commencé à s'intéresser spécifiquement à ces habiletés motrices pour tenter de comprendre leur apport dans l'acquisition des concepts numériques. Les recherches menées sur cette question restent toutefois peu nombreuses et les résultats trop souvent contradictoires pour pouvoir définir précisément la nature des HSM des doigts impliquées dans les traitements numériques ainsi que les mécanismes qui sous-tendent ces relations.

La présente thèse vise à mieux comprendre **la contribution des doigts dans le développement des compétences numériques et arithmétiques typique et atypique**. Les questions portant sur le rôle des HSM seront au cœur de ce travail de recherche qui se compose de trois parties distinctes. La **première partie** vise à **faire un état des lieux des recherches menées** à ce jour sur notre thématique. Nous décrirons, dans une première revue narrative **(chapitre 1)**, les évidences empiriques qui caractérisent le développement des compétences numériques et arithmétiques. Une seconde revue narrative **(chapitre 2)** sera dédiée aux évidences qui caractérisent le rôle des doigts à l'acquisition des symboles numériques verbaux. L'identification et la synthèse des études qui ont ciblé les compétences arithmétiques ont, quant à elles, fait l'objet d'une revue méthodique qui sera proposée au lecteur dans le troisième chapitre **(chapitre 3)** de cette première partie.

La **seconde partie** de la thèse rassemble deux études expérimentales menées auprès d'enfants au développement typique âgés de 3 à 8 ans. Ces deux études ont pour objectif de **clarifier le rôle des HSM sur le développement des compétences arithmétiques ainsi que les processus sous-jacents à cette relation**. A l'heure actuelle, les recherches menées sur cette question se sont focalisées essentiellement sur deux catégories d'HSM: les gnosies digitales et les habiletés motrices fines qui se réfèrent respectivement à la capacité à se représenter mentalement et à bouger de manière différenciée ses propres doigts (Barrocas et al., 2020; Noël, 2005). L'apport des HSM a été examinée au moyen d'études observationnelles qui ont montré l'existence d'une relation directe avec les compétences numériques précoces et les habiletés arithmétiques (Asakawa & Sugimura, 2014; Barnes et al., 2011; Fayol et al., 1998; Fischer et al., 2018; Newman, 2016; Noël, 2005) ainsi que par le biais d'études interventionnelles par lesquelles un lien de causalité entre ces variables a pu être établi (Asakawa et al., 2019; Gracia-Bafalluy & Noël, 2008; voir Schild et al., 2020 pour des résultats contradictoires). Face à ces premières investigations, Asakawa et Sugimura (2022) sont allés un pas plus loin dans la réflexion en confirmant les résultats des études antérieures ainsi qu'en examinant les mécanismes impliqués dans cette relation. Par la conduite d'analyses de médiation, ils ont ainsi confirmé que les habiletés motrices fines contribuaient directement à l'acquisition des compétences arithmétiques mais également que cette relation pouvait être médiée par la maitrise du comptage verbal, chez les enfants de maternelle.

Les deux études expérimentales décrites dans cette partie ont été conduites en suivant une approche similaire à celle proposée par Asakawa et Sugimura (2022). La première étude (**chapitre 4**) visait à tester l'hypothèse fonctionnaliste qui suggère que les HSM contribueraient au développement des compétences arithmétiques par une relation fonctionnelle (Butterworth, 1999). Pour tester cette hypothèse, nous avons examiné si la relation entre HSM et performances arithmétiques pouvait être médiée par la capacité à utiliser ses doigts dans une tâche de calcul. Ces travaux ont été menés en utilisant un design longitudinal de manière à capter les changements développementaux des variables en jeux et ainsi fournir une meilleure compréhension de leurs trajectoires développementales et des prédicteurs à ces trajectoires. Il est attendu que l’évolution des HSM prédise le développement des compétences arithmétiques. Par ailleurs, si l'hypothèse fonctionnaliste se vérifie, le développement des HSM pourrait soutenir l'usage du comptage sur les doigts ce qui contribuerait, par conséquent, au développement des compétences arithmétiques de l’enfant. La seconde étude de cette première partie (**chapitre 5**) s'inscrivait dans le développement numérique précoce et visait à examiner si les HSM contribuent à l’acquisition des compétences arithmétiques par la maitrise des concepts cardinaux. Comme les tâches utilisées traditionnellement pour évaluer les habiletés motrices fines sont multi-déterminées, une attention particulière a été portée, dans cette recherche, sur l'identification des composantes motrices spécifiquement impliquées dans l'exécution des gestes numériques. Des analyses du mouvement en 3D ont ainsi été menées de manière à obtenir des mesures fines des mouvements de la main. Si l'utilisation des doigts joue un rôle dans le développement des compétences cardinales de l'enfant, il est attendu que la maitrise des concepts cardinaux soit un médiateur significatif de la relation entre HSM et compétences arithmétiques.

Dans le champ de la cognition numérique, certaines recherches sont menées auprès d'enfants avec des troubles neuro-développementaux ou des lésions cérébrales précoces afin de mieux identifier les domaines affectés par ces troubles. La **troisième partie** de cette thèse traite notre thématique de recherche sous cette perspective. En travaillant auprès d'enfants qui présentent des troubles neuro-développementaux altérant l'acquisition et le développement des HSM (i.e., trouble développemental de la coordination (TDC), infirmité motrice cérébrale (IMC)), les deux études expérimentales menées dans cette partie visent à **explorer les conséquences de ces altérations motrices sur leurs traitements numériques et à proposer, le cas échéant, des pistes d'intervention**. A ce jour, aucune recherche n'a encore été conduite pour tester l'hypothèse selon laquelle les déficits moteurs de ces enfants pouvaient contribuer aux difficultés qu'ils rencontrent dans les traitements numériques (e.g., de Freitas Feldberg et al., 2021; Gomez et al., 2015, 2016; Jenks et al. 2007, 2009) par une altération du comptage sur les doigts. Pourtant, le comptage sur les doigts revêt d'une importante particulière puisqu'il permet à l'enfant de garder une trace de son comptage pour soulager la charge en mémoire de travail inhérente à certains traitements numériques complexes telles que la résolution de calculs (Crollen et al., 2011; de Chambrier et al., 2018; Passolunghi & Cornoldi, 2008). Lorsque la mémoire de travail fait défaut, comme c'est souvent le cas chez les enfants avec des troubles des apprentissages en mathématiques, l'usage des doigts est d'ailleurs plus intense et continue à être observé jusqu'à tard dans le développement (Geary & Brown, 1991; Jordan et al., 2003; Noël, 2005; Passolunghi & Cornoldi, 2008; Wylie et al., 2012). En plus d'une altération motrice, un déficit en mémoire de travail a très souvent été mis en évidence chez les enfants TDC et IMC (i.e., Alloway & Archibald, 2009; Rigoli et al., 2013; Stadskleiv et al., 2018). Cette comorbidité de symptômes pourrait être particulièrement délétère pour ces enfants qui pourraient alors moins bénéficier de leurs doigts pour alléger leur mémoire de travail lorsqu'ils doivent résoudre des problèmes complexes. Dans les cas les plus sévères, le recours au comptage sur les doigts pourrait alors être déconseillé et des solutions alternatives devront être proposées à l'enfant pour rendre les traitements numériques efficients.

C'est dans ce cadre théorique que s'inscrivent les deux études expérimentales décrites dans cette troisième partie. La première (**chapitre 6**) visait à investiguer la fonctionnalité du comptage sur les doigts chez les enfants TDC. Il s'agissait d'examiner si ces enfants tiraient profit du comptage sur les doigts pour résoudre une tâche numérique à forte charge en mémoire de travail. En utilisant des techniques d'analyse du mouvement en 3D, la qualité des gestes exécutés par ces enfants pendant la tâche a également été examinée afin de définir si les erreurs relevées pouvaient être causées par des gestes dysfonctionnels. Comme les enfants TDC présentent des déficits moteurs importants, il était attendu que le comptage sur les doigts soit moins efficace chez ces enfants en comparaison à leurs pairs au développement typique, pour résoudre ce type de tâche. La qualité des gestes exécuté par les enfants pourrait, par ailleurs, être altérée ce qui pourrait entrainer des erreurs de comptage lors du traitement de la tâche. La seconde étude (**chapitre 7**) visait à évaluer l'efficacité, la spécificité et les effets de généralisation d'une rééducation du calcul menée auprès de NG, un enfant IMC présentant un handicap moteur associé à un déficit en mémoire de travail. Lourdement handicapé, NG n'était pas en mesure d'utiliser le comptage sur les doigts pour soulager sa mémoire de travail dans les traitements numériques. Le recours au matériel de manipulation n'était pas efficient. Ancrée dans l'Evidence-Based Practice (EBP), cette intervention a été conçue pour répondre aux besoins spécifiques de l'enfant en utilisant un matériel adapté à son handicap comme alternative aux doigts. A l'issue de cette rééducation, il était attendu que les compétences arithmétiques de NG s'améliorent et que ces progrès soient dus à l'intervention et non à un développement cognitif général. En outre, par un effet de généralisation, une amélioration de compétences numériques non ciblées mais intrinsèquement liée à l'intervention était attendue (e.g., calcul mental).

Partie 1 : Etat de l’art

Chapitre 1 - Le développement des compétences numériques et arithmétiques.

1 Première appréhension de la quantité

Le développement numérique est un processus lent qui ne se limite pas uniquement aux apprentissages scolaires mais qui est présent chez l'enfant dès ses premiers instants de vie. A ce stade de développement, il réalise des traitements numériques rudimentaires, proches de ceux observés chez les animaux tels que le macaque (Brannon & Terrace, 2000) ou encore le rat (Meck & Church, 1983). Comme les nourrissons ne disposent pas encore de compétences langagières, les études menées avec eux sont conçues à partir de paradigmes d'habituation qui reposent sur la capacité qu'ont ces jeunes enfants à détecter des changements qui surviennent dans leur environnement. Par ce type de paradigme, les auteurs ont ainsi montré que les nourrissons étaient capables de distinguer des collections d'objets de tailles différentes. En 1983, dans une des premières études menées sur la question, Antell et Keating ont apporté la preuve que, dès la naissance, les nourrissons étaient en mesure de discriminer des collections de petite numérosité (i.e., 2 *vs* 3) sans pour autant parvenir à distinguer deux collections de plus grande numérosité (i.e., 4 *vs* 6). Il faudra attendre environ 6 mois pour que l'enfant puisse être en mesure de faire cette distinction (i.e., discriminer 8 *vs* 16 ; Libertus & Brannon, 2010; Xu & Spelke, 2000). La compréhension des relations quantitatives de type « plus petit que » ou « plus grand que » arrive, quant à elle, un peu plus tard dans le développement. Vers 11 mois, l'enfant est ainsi en mesure de faire la distinction entre des séquences de plusieurs collections de numérosité croissante et des séquences de numérosité décroissante, ce qui montre leur capacité à percevoir des relations d'ordinalité entre les ensembles (Brannon, 2002).

A l'heure actuelle, deux mécanismes sont évoqués par les chercheurs pour expliquer que de telles capacités puissent être présentes si tôt dans le développement. Un premier mécanisme, nommé Object Tracking System (OTS) et évoqué par Trick et Pylyshyn (1994) pourrait expliquer la capacité qu'ont les nouveaux nés à discriminer les petites numérosités. Selon cette théorie, l'enfant disposerait de marqueurs spatiaux (FINSTs) qui lui permettraient de garder une trace mentale des objets placés simultanément dans son champ visuel et de suivre leurs trajectoires lorsqu'ils sont en mouvement. Lorsque le nourrisson doit discriminer précisément deux collections d'objets, il mettrait alors en correspondance leurs traces mentales de manière à les comparer sans devoir appréhender la quantité en tant que telle. Il s'agit là d'un mécanisme automatique et inconscient qui est très restreint puisqu'il se limite au traitement de petites collections ne comprenant pas plus de 3 ou 4 objets.

La discrimination de collections de plus grandes numérosités est, quant à elle, possible grâce au mécanisme de représentation approximative de la quantité (connu sous le nom d'Approximate Number System, ANS ; Dehaene, 1997). Ce mécanisme, présent très tôt dans le développement, se fonde sur une approche intuitive de la quantité offrant à l'enfant la possibilité de distinguer des collections sans avoir à en compter individuellement les éléments. Les recherches ont montré que la discrimination des grandes quantités obéit à la loi de Weber qui suggère que la discriminabilité de deux ensembles (e.g., 8 *vs* 16 objets) ne dépendrait pas de la différence de taille entre les quantités traitées (i.e., 16-8=8) mais plutôt de leur rapport (i.e., 8 :16=½). Plus le rapport entre les quantités est proche de 1, plus il sera difficile de les dissocier. Ainsi, à 6 mois, l'enfant est capable de discriminer des collections sur base d'un ratio de 1/2 (e.g., 8 *vs* 16) mais il échoue lorsque le ratio est de 2/3 (16 *vs* 24) (Brannon et al., 2006; vanMarle & Wynn, 2006; Xu et al., 2005; Xu & Spelke, 2000). Certains travaux suggèrent que ce rapport minimal de discrimination évoluerait dans le temps puisqu'à 9 mois, les enfants semblent en mesure de discriminer des collections avec un ratio de 2/3 mais pas de 4/5 (Lipton & Spelke, 2003).

En somme, l'ensemble de ces travaux montrent que certains aspects de la notion de quantité sont présents chez l'enfant dès la naissance, bien avant le moindre apprentissage formel. Ces traitements numériques restent toutefois très élémentaires puisqu'ils sont approximatifs ou limités à de petites quantités. Ces dernières ne pourront être traitées précisément par l'enfant qu'à partir du moment où il commencera à acquérir ses toutes premières compétences langagières.

2 Découverte des codes symboliques numériques

2.1 Le code verbal

2.1.1 Apprentissage de la chaine numérique verbale

L'enfant apprend ses premiers symboles verbaux vers 2 ans, alors qu'il vit une véritable explosion langagière. Durant cette période, il produit quotidiennement des mots-nombres qu'il emploie comme des articles définis sans se référer à la quantité qu'ils représentent (Krajewski & Schneider, 2009). L'apprentissage de ces mots s'opère alors de manière incidente et est lié aux activités quotidiennes de l'enfant (Wynn, 1990). Vers 2 ans et demi, ce dernier fait ses premiers pas à l'école où il va apprendre des séquences de mots ayant un ordre précis (e.g., jours de la semaine, mois de l'année, saisons). Il se montre alors capable d'apprendre rapidement et facilement ce type de routine ce qui favorisera son entrée dans les activités de comptage durant lesquelles il devra réciter les mots-nombres dans un ordre précis pour former la chaine numérique verbale (Wynn, 1990). D'abord constituée de quelques unités, cette chaine va progressivement s'accroitre de sorte que l'enfant soit capable de compter de plus en plus loin (Fuson et al., 1982). L'apprentissage de cette séquence se fera au travers de deux phases développementales : une phase d'acquisition, plutôt précoce, et une phase d'élaboration, plus tardive (Fuson 1988).

Au cours de la phase d'acquisition, l'enfant apprend à énoncer la chaine numérique verbale correctement. Les mots-nombres sont alors appris comme une série d'étiquettes. En comparant les essais successifs de comptage chez de jeunes enfants, Fuson et al. 1982 ont mis en évidence trois parties distinctes dans les séquences produites. La partie *stable et conventionnelle* contient les mots-nombres que l'enfant est capable de réciter à plusieurs reprises, dans l'ordre attendu (e.g., Essai 1 : « un, deux, trois »/ Essai 2 : « un, deux, trois »). La partie *stable et non conventionnelle* se réfère aux mots-nombres que l'enfant énonce à plusieurs reprises, dans un ordre aléatoire (e.g., Essai 1 : « quatre, cinq, sept »/ Essai 2 : « quatre, cinq, sept »). Entre 3 et 5 ans, cette partie contient essentiellement des omissions, des répétitions et des inversions de mots (Fuson, 1988). Enfin, la partie *non stable et non conventionnelle* contient les mots-nombres produits de manière inconstante et dans un ordre aléatoire (e.g., Essai 1 : « neuf, douze, vingt »/ Essai 2 : « dix, quinze, vingt »).

Au fur et à mesure du temps, l'enfant sera amené à développer la partie stable et conventionnelle de la chaine numérique verbale au détriment des deux autres parties. L'extension de cette partie est facilitée par la régularité de la langue. Ainsi, l'apprentissage de la chaine numérique verbale est plus long chez des enfants anglophones que chez les enfants chinois puisque, contrairement aux langues asiatiques régulières et structurées en base-10, l'anglais comporte de nombreuses irrégularités (Miura & Okamoto 2003). Alors que 10 mots suffisent à un enfant chinois pour compter jusqu'à 99, le jeune anglophone devra, lui, apprendre 20 mots différents pour parvenir à compter jusqu'à 20 (Fuson & Kwon, 1992). En français, la structure linguistique est irrégulière jusqu'à 16. L'apprentissage de la chaine numérique verbale se fera donc par extension de la partie stable et conventionnelle jusqu'à ce nombre. Au-delà, l'enfant s'appuie sur des règles de composition linguistique. Il comprend ainsi qu'il suffit d'associer le nom d'une dizaine avec des unités allant de 1 à 9 pour former facilement une série de nouveaux mots-nombres. A ce stade, il n'est pas rare d'observer des erreurs d'omissions de dizaines (e.g., « vingt-huit, vingt-neuf, quarante, quarante et un… ») ou encore de voir certains enfants arrêter leur comptage à la fin d'une dizaine, ne sachant pas le nom de la dizaine suivante (Siegler & Robinson, 1982).

Parallèlement à la phase d'acquisition de la chaine numérique verbale, l'enfant va commencer à élaborer sa séquence. Il apprend alors que la comptine numérique est composée de plusieurs mots distincts qui entretiennent des relations étroites entre eux. Fuson et al. (1982) distinguent cinq niveaux de développement chez l'enfant. Au niveau *chapelet*, La chaine numérique est apprise par cœur comme un tout indifférencié (*undeuxtroisquatrecinq*). L'enfant ne parvient pas à associer un mot à un objet et commence systématiquement à réciter sa comptine à partir de 1. Au *niveau de la chaine insécable*, les mots-nombres sont différenciés mais l'enfant ne compte qu'à partir de 1 (*un, deux, trois, quatre, cinq*) et n'est en mesure de produire que des séquences croissantes. Il se montre également capable d'arrêter son comptage à une borne définie. Le *niveau de la chaine sécable* marque le début de la compréhension du lien entre les mots-nombres. L'enfant peut initier son comptage à partir de n'importe quel endroit de la chaine. Il est, par ailleurs, capable de compter entre deux bornes ce qui implique de garder en mémoire la borne supérieure et d'arrêter le comptage au bon moment. À ce stade, l'enfant commence également à compter à rebours et peut retrouver le mot-nombre qui vient juste avant ou juste après une cible. Au niveau de la *chaine dénombrable*, les mots-nombres deviennent des unités à part entière que l'enfant peut dénombrer. Il est ainsi en mesure de compter *x* pas à partir d'un nombre donné ou encore d'indiquer le nombre de pas qui se trouvent entre deux nombres (e.g., « Pour aller de cinq à neuf, je dois faire six, sept, huit, neuf. Il y a donc quatre pas entre cinq et neuf »). Les mots-nombres peuvent ainsi être additionnés ou soustraits. Enfin, *au niveau de la chaine bidirectionnelle,* la séquence numérique est parfaitement maitrisée à l'endroit aussi bien qu'à rebours. L'enfant est capable de changer la direction de son comptage rapidement et de façon flexible.

Il faudra plusieurs années à l'enfant pour acquérir une bonne maitrise de la chaine numérique verbale. Un chevauchement partiel entre deux phases est donc très souvent observé. Ainsi, la partie initiale de la séquence verbale peut être en cours d'élaboration alors même que les parties ultérieures sont encore en voie d'acquisition (Gould, 2016).

2.1.2 Principes de dénombrement et acquisition de la valeur cardinale des mots-nombres

Une bonne maitrise de la chaine numérique verbale est nécessaire à l'enfant s'il veut réaliser correctement les activités de dénombrement qui consistent à mettre en correspondance le pointage des objets d'une collection avec la récitation de la chaine numérique verbale afin de déterminer précisément le nombre d'éléments qu'elle contient (Wynn, 1990). C'est par l'application de cette procédure que le jeune enfant parvient à répondre à la question « Combien ? » à laquelle il est très souvent confronté dans sa vie quotidienne. La procédure de dénombrement est sous-tendue par l'acquisition de cinq principes fondamentaux décrits par Gelman et Gallistel (1978) :

- Le principe de *correspondance terme à terme* selon lequel à chaque objet doit être associé à un unique mot-nombre énoncé.
- Le principe de *l'ordre stable et conventionnel* selon lequel les mots-nombres doivent toujours être énumérés dans le même ordre. Ce principe tient à l'acquisition de la chaine numérique verbale.
- Le principe de *cardinalité* qui permet à l'enfant de comprendre que le dernier mot-nombre énoncé se réfère à l'ensemble des objets présents dans une collection et non pas au dernier élément compté.
- Le principe *d'abstraction* qui se réfère au fait que l'activité de dénombrement est possible quelles que soient les caractéristiques individuelles des objets de la collection traitée.
- Le principe de *non pertinence de l'ordre* selon lequel le résultat du dénombrement est le même quel que soit l'objet par lequel l'enfant commence son comptage. L'acquisition de ce dernier principe permettra à l'enfant de dissocier le dénombrement d'une simple activité d'étiquetage.

Pour répondre à la question « Combien ? », l'enfant comprend assez rapidement qu'il doit répéter le dernier mot-nombre qu'il a énoncé lors du dénombrement. Cette réponse est toutefois très souvent donnée en dépit d'une compréhension profonde de la quantité qu'il représente. Un enfant de 3 ans peut ainsi être en mesure de dénombrer une collection qui contient plus que 4 objets et donner une réponse correcte à la question "Combien?" sans pour autant parvenir à former une collection de numérosité équivalente lorsque cela lui est demandé (Frye et al., 2016; Sarnecka et al., 2007; Sarnecka & Carey, 2008). En conséquent, les auteurs suggèrent que l'acquisition de la signification cardinale du mot-nombre apparait tardivement (Sarnecka & Carey, 2008) et indépendamment de la compréhension de la procédure de dénombrement (Wynn, 1992).

C'est entre de 3 et 6 ans que l'enfant acquière la maitrise de la valeur cardinale des mots-nombres. Il est alors en mesure de comprendre que le dernier mot-nombre énoncé dans une tâche de dénombrement se réfère à l'ensemble des objets d'une collection et pas uniquement au dernier élément compté (Gelman & Gallistel, 1978).

Ces dernières décennies, un nombre considérable de recherches se sont intéressées au développement de cette compétence chez l'enfant (e.g., Le Corre et al., 2006; Rousselle & Vossius, 2021; Sarnecka & Carey, 2008; Wynn, 1992). Dans la plupart de ces travaux, la maitrise des mots-nombres a été évaluée par la tâche "Donne-moi *n*" décrite par Wynn (1990, 1992) et considérée, depuis lors, comme une tâche de référence pour mesurer le niveau de développement cardinal de l'enfant. Lors de la passation de cette tâche, l'expérimentateur propose à l'enfant de se placer devant une boite contenant des objets. L'adulte demande ensuite à l'enfant de lui donner un nombre défini d'objets (e.g., « Peux-tu me donner *n* jouet(s)? »). Si l'enfant parvient à répondre correctement à la demande, une collection de *n+1* objets lui est demandée à l'essai suivant. En cas d'échec, l'expérimentateur demande à l'enfant de produire une collection de *n-1* objets à l'essai suivant de manière à s'assurer de la stabilité de sa performance. La tâche prend fin quand l'enfant parvient à donner à deux reprises la numérosité *n* et échoue à deux reprises pour la numérosité *n+1*. Le niveau cardinal de l'enfant est alors défini comme le plus grand mot-nombre auquel l'enfant est capable d'associer une numérosité correcte.

Contrairement à ce que nous pourrions penser au premier abord, l'acquisition de la valeur cardinale des mots-nombres se développe progressivement, par paliers successifs (Le Corre et al., 2006; Sarnecka & Carey, 2008; Wynn, 1990). Lorsque l'enfant se situe au niveau le plus précoce, il ne fait pas de distinction entre les différents mots-nombres. Ainsi, lorsque l'expérimentateur lui demande de lui donner *n* objets, l'enfant lui tend, soit un seul objet, soit une poignée d'objets. Vers 3 ans, l'enfant est capable de réaliser convenablement la tâche lorsqu'il s'agit de donner un seul objet. En revanche, la tâche est échouée lorsque l'expérimentateur lui demande plus d'un objet. Dans la littérature anglophone, l'enfant sera appelé un « *one-knower* » (Le Corre et al., 2006). Plusieurs mois plus tard, l'enfant se révèle compétent dans la tâche lorsqu'il s'agit de donner deux objets mais pas trois puis trois objets mais pas quatre. Il sera alors considéré comme un « *two-knower* » ou un « *three-knower* » selon son niveau de développement cardinal. Selon Wynn (1992), il faut 4 à 5 mois environ pour que l'enfant progresse d'un niveau. A ce stade de développement, il n'est capable de réaliser la tâche qu'avec de petites quantités (Wynn, 1990). Il n'a alors acquis que partiellement le principe de cardinalité car il ne maitrise la cardinalité que d'un sous-ensemble d'éléments. L'enfant sera alors considéré comme étant un « *Subset-knower* » (Le Corre et al., 2006; Le Corre & Carey, 2007). Il restera à ce stade de développement pendant une période qui peut durer jusqu'à plus d'un an. Puis, vers 4 ans, il se révèlera capable de généraliser ses connaissances en parvenant à réaliser la tâche pour l'ensemble des collections proposées, quelle que soit leur numérosité. Il semble que l'enfant acquiert cette compétence simultanément pour l'ensemble des mots-nombres de la chaine numérique verbale contrairement aux stades précédents qui se sont développés successivement (Sarnecka & Carey, 2008). Selon Le Corre et al. (2006), le principe de cardinalité n'est acquis que lorsque l'enfant a atteint ce dernier stade de développement. Il sera alors qualifié de « *Cardinal-Principle-knower* ». En évaluant un large échantillon d'enfants francophones, Rousselle et Vossius (2021) ont récemment suggéré que cette phase de compréhension de la cardinalité prendrait plus de temps qu'initialement postulé par Wynn 1990.

2.2 Le code arabe : Système positionnel et base-10

Vers 4 ou 5 ans, alors qu'il commence tout juste à maitriser les règles qui régissent le code verbal et le sens des mots-nombres, le jeune enfant découvre un nouveau code symbolique : le code arabe. Constitué de 10 symboles (chiffres de 0 à 9) combinables à l'infini, ce nouveau code devra être acquis par l'enfant pour procéder à des traitements numériques complexes. La maitrise d'un tel code passe non seulement par un apprentissage lexical par lequel les mots-nombres de 0 à 9 sont associés aux chiffres mais également par un apprentissage syntaxique qui définit les règles à respecter pour former des nombres à plusieurs chiffres. L'enfant apprendra alors qu'aucun nombre ne commence par un 0 et que les chiffres peuvent prendre une valeur différente selon la place qu'ils occupent dans le nombre, découvrant ainsi le principe de la numération positionnelle.

Selon l'hypothèse développementale proposée par Cheung et Ansari (2021), le développement de la signification des nombres à plusieurs chiffres se déroulerait en trois temps. En premier lieu, l'enfant doit être en mesure d'identifier le nombre à deux chiffres comme un nombre à part entière (65) et non comme deux nombres distincts positionnés l'un à côté de l'autre (6 et 5). Par la suite, il doit comprendre qu'il y a autant de positions dans le nombre que de chiffres et que la valeur de chaque position augmente de gauche à droite. Enfin, au stade le plus avancé, l'enfant doit appréhender l'idée selon laquelle la valeur précise de chaque position est déterminée par la base-10. Chaque position dans le nombre représente ainsi une puissance de 10 qui augmente de 1 à chaque déplacement vers la gauche : de 10^0 pour les unités, à 10^1 pour les dizaines, à 10^2 pour les centaines etc… Dès lors, la maitrise du système positionnel (Etape 2) et la maitrise de la base-10 (Etape 3) font référence à deux construits distincts mais interdépendants (Mix et al., 2022).

La maitrise du système positionnel est cruciale, notamment lorsque deux nombres à plusieurs chiffres doivent être comparés (Nuerk et al., 2001). Comme l'étude des grands nombres n'est abordée explicitement qu'à l'école primaire, d'aucun serait tenté de croire qu'aucun traitement numérique sur ce type de nombres ne serait possible chez des enfants plus jeunes. En 2014, Mix et al. ont pourtant prouvé le contraire en demandant à des enfants âgés de 3 à 7 ans de comparer des paires de nombres écrits à plusieurs chiffres. Les résultats ont montré que, avant de faire leur entrée dans l'enseignement formel, les enfants disposaient de connaissances sur la valeur de la position du chiffre dans le nombre. En effet, dès l'âge de 5 ans, ils étaient en mesures de comprendre que le nombre se lit de gauche à droite, que la magnitude du nombre dépend du nombre de chiffres qu'il contient (256 > 14) et que le même chiffre représente une quantité plus importante lorsqu'il se trouve à gauche du nombre plutôt qu'à droite (<u>3</u>24 >15<u>3</u>). A partir d'une méthodologie similaire, Yuan et al. (2019) ont récemment dupliqué ces résultats et montré que la maitrise des concepts du système positionnel se développe entre l'âge de 5 et 6 ans et qu'elle est précédée d'un an par la lecture des nombres écrits.

A ce stade de développement, la maitrise du système positionnel est indépendante de la compréhension de la base-10 (Mix et al., 2022). Un enfant pourrait ainsi comparer correctement 81 et 18 en se basant sur les propriétés du système positionnel sans pour autant comprendre que le 8 dans 81 occupe une position de dizaine et qu'il peut être représenté par 8 blocks de 10 unités alors que le 8 dans le nombre 18 sera représenté par 8 unités. Il faudra attendre son entrée en 1ère année de primaire pour que l'enfant commence à acquérir les principes de la base-10.

A partir des stratégies que certains enfants mettent en place pour résoudre des problèmes additifs et soustractifs, Fuson et al. (1997) ont proposé le modèle UDSSI qui décrit cinq structures conceptuelles que l'enfant peut acquérir face aux nombres à deux chiffres (Figure 1) :

- La *conception unitaire* des nombres à deux chiffres (Figure 1a) : Lors de cette phase, le nombre est vu comme un ensemble d'unités indivisibles et les chiffres ne sont pas séparables. Ainsi 24 est perçu comme 24 unités et non pas comme 2 dizaines et 4 unités. Cette conception est favorisée par l'absence de transparence de la langue française qui, contrairement à la langue chinoise, ne permet pas de marquer de rupture après le 10.
- La *conception dizaines-unités* basée sur le code verbal (Figure 1b) : A ce stade, l'enfant va commencer à séparer le nombre verbal (« vingt-quatre ») en deux parties. Une partie est consacrée aux dizaines (« vingt ») tandis que l'autre partie est consacrée aux unités (« quatre »). Chaque partie étant considérée comme un groupe de « uns ». A ce titre, les unités incluses dans les dizaines sont considérées comme étant séparées des unités incluses dans les unités.
- La conception des *séquences de dizaines-unités* (Figure 1c) : L'enfant commence à percevoir les dizaines comme des groupes de 10 unités. Malgré tout, la trace des unités persiste dans chaque groupe de 10.
- La conception des *dizaines-unités séparées* (Figure 1d): A ce niveau, les groupes de 10 sont perçus comme des entités d'un ordre supérieur. Ainsi, 40 n'est plus vu comme un groupe de 40 unités mais comme 4 dizaines.
- La conception *intégrée dizaine-unité* : L'enfant est capable de passer d'une conception à l'autre aisément. La dizaine peut donc être perçue tantôt comme un groupe de dix unités, tantôt comme une unité d'ordre supérieur.

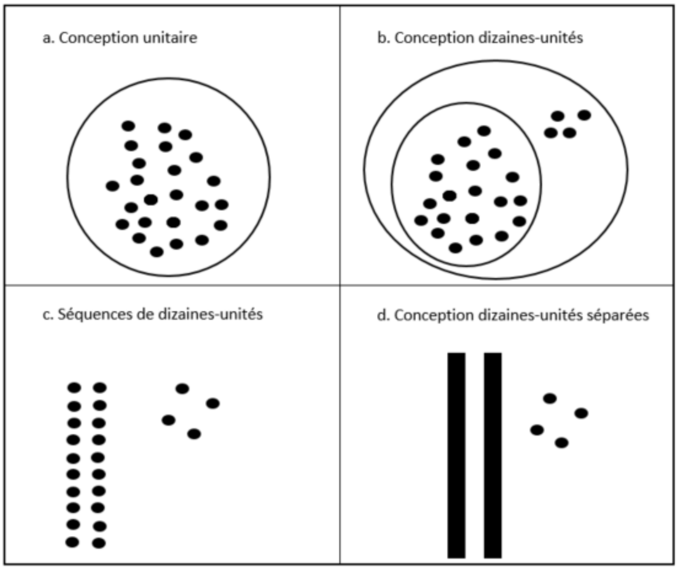

Figure 1. Conceptions du nombre à deux chiffres

La maitrise des nombres à plusieurs chiffres est sans doute l'une des compétences les plus importantes du développement numérique. Par conséquent, les enfants qui rencontrent des difficultés en mathématiques présentent souvent une faible maitrise du système positionnel et de la base-10 (Chan et al., 2014; Gervasconi & Sullivan, 2007; Hanich et al., 2001). Si ces compétences ont une place si importante, c'est parce qu'elles sont fondamentales pour aborder les traitements numériques complexes tels que la résolution de problèmes arithmétiques (Moeller et al., 2011).

3 L'arithmétique

3.1 Le développement des compétences arithmétiques

Alors que le jeune enfant d'à peine 5 mois semble déjà comprendre le concept d'ajout et de retrait (Wynn, 1992; voir Christodoulou et al., 2017 pour une méta-analyse), il faudra attendre l'âge de 2 ans et demi pour que celui-ci soit en mesure de réaliser des traitements arithmétiques plus formels. A cet âge, il n'est évidemment pas attendu que l'enfant soit capable de résoudre des problèmes arithmétiques symboliques tels que 5+3=8. Cependant, il commence déjà à appréhender les règles qui sous-tendent les opérations additives et soustractives. La première règle avec laquelle l'enfant se familiarise est celle qui régit la *fonction de succession* selon laquelle additionner ou soustraire un item à une collection d'objets implique un déplacement d'un pas en avant ou d'un pas en arrière dans la chaine numérique verbale (Le Corre, 2014; Sarnecka & Carey, 2008). Ainsi, lorsque l'enfant maitrise la *fonction de succession*, il est en mesure de comprendre que l'ajout d'un bonbon à une collection qui en contient 3 signifie que la collection est désormais constituée de 4 bonbons, soit le mot-nombre qui suit directement « trois » dans la chaine numérique verbale. La découverte de cette règle est un premier pas vers l'arithmétique simple.

Aux alentours de trois ans, l'enfant se montre capable de réaliser des traitements arithmétiques exacts impliquant des petites quantités. Dans la majorité des cas, il lui sera demandé de réaliser des opérations sur des représentations non-symboliques du nombre (Levine et al., 1992). L'évaluation se déroule alors comme suit : En premier lieu, une collection d'objets (2 jetons) est présentée à l'enfant puis cachée derrière un écran. Une seconde collection (3 jetons) lui est ensuite présentée avant d'être, à son tour, cachée derrière l'écran. Alors que les jetons restent masqués, l'enfant est invité à reproduire avec ses propres jetons une collection équivalente à celle formée par les deux premières collections (5 jetons). Les traitements arithmétiques pourront également se faire à partir de mots-nombres (ex: Noël, 2009). Il est alors demandé à l'enfant de résoudre des problèmes verbaux tels que : « Dans cette cage, il y a deux oiseaux. Si un autre oiseau rentre dans la cage, peux-tu me dire combien il y a d'oiseaux en tout ? ». Pour répondre à la question, certains enfants utiliseront un support concret (jetons, doigts) pour représenter les quantités impliquées dans le problème. Vers 5 ans, alors qu'il se trouve en dernière année de maternelle, l'enfant peut réaliser des traitements arithmétiques approximatifs pour résoudre des problèmes impliquant de grandes quantités ou encore des nombres arabes qu'il ne connait pas. En 2006, Barth et al. ont proposé une tâche d'addition non-symbolique pour prouver l'existence de telles compétences chez de si jeunes enfants. La tâche se déroule en deux temps. En premier lieu, deux collections de points bleus (12 et 7) sont présentées successivement à l'enfant puis cachées derrière un écran. Une troisième collection de points rouges (16) est ensuite affichée à l'écran. L'enfant est invité à dire si la collection de points rouges est plus petite ou plus grande que les deux collections de points bleus réunies derrière l'écran et cachées de l'enfant (12+7). La capacité à traiter approximativement des problèmes arithmétiques a également été montrée chez des enfants de cet âge à partir d'une tâche impliquant le traitement de nombres arabes supérieurs au niveau de développement cardinal des participants (Lê & Noël, 2021). Les enfants étaient alors invités à estimer le résultat d'une addition de deux nombres arabes et à le comparer avec un troisième (ex : 4+5 est-il plus grand que 7 ?).

Vers 6 ans, l'enfant entre en première année de primaire. Il apprend alors à résoudre des calculs écrits. Les premiers apprentissages concernent les problèmes additifs qu'il pourra résoudre en utilisant des stratégies procédurales basées sur le comptage. Certaines de ces stratégies, classées par ordre de maturité, ont été décrites par Groen et Parkman en 1972. La stratégie la plus précoce est celle du *comptage tout* (nommée *counting all* dans la littérature anglophone). Lorsqu'il utilise cette stratégie, l'enfant compte un à un tous les éléments impliqués dans le calcul pour en définir la somme. Il commence ainsi son comptage à partir 1 et le poursuit, par pas de 1, pour chacun des deux termes du calcul (2+3 = 1,2 et 3, 4, 5). A ce stade, il s'appuie souvent sur des objets concrets pour représenter les termes de l'addition. Dans notre exemple, il comptera ainsi 2 jetons, puis 3 jetons avant de compter de nouveau l'ensemble des objets présents devant lui. Immature, cette stratégie est très coûteuse en terme de temps. A un stade de maturité plus avancé, l'enfant utilisera la stratégie du *comptage sur* (*counting on*). Dans ce cas, il commencera son comptage à partir du premier terme de l'addition et le poursuivra, par pas de 1, jusqu'à l'ajout du second terme (ex : 2+3 = 2 puis 3,4,5). Enfin, la stratégie du *comptage min* (*counting min*) est la stratégie de comptage la plus mature et la plus économique observée chez les jeunes enfants. A ce stade, l'enfant commence son comptage par le plus grand des deux termes puis le poursuit, par pas de 1, jusqu'à l'ajout du second terme (2+3 = 3 puis 4, 5).

En fin de première année de primaire et durant les années suivantes, l'enfant se familiarise avec des stratégies de calcul plus sophistiquées à partir desquelles il pourra résoudre les calculs sans recourir au comptage. La stratégie dite de *récupération des faits arithmétiques* est la plus intéressante puisqu'elle nécessite peu de ressources cognitives et contribue à accélérer la vitesse de résolution. Par l'exposition répétée à certains calculs, l'enfant apprend à associer des petits problèmes (ex : 2+3) à leurs résultats (ex : 5). Ces associations forment un réseau de faits arithmétiques qui seront stockés en mémoire à long terme et récupérés automatiquement lorsque l'enfant est confronté au problème (Campbell, 1994). Les premiers faits arithmétiques appris concernent essentiellement les calculs impliquant de petites quantités ou encore deux termes identiques (ex : 5+5). En suivant des enfants belges néerlandophones pendant deux ans, soit entre la 1ère et la 3ème primaire, Vanbinst et al. (2015), ont mis en évidence trois profils d'enfants qui se distinguent par leur niveau de maitrise des faits arithmétiques : (1) les enfants lents et avec un temps d'exécution variable, (2) les enfants avec un temps d'exécution moyen et (3) les enfants efficients. Même si les enfants lents s'améliorent au cours du temps, cette progression n'est pas suffisante pour atteindre une efficience comparable à leurs pairs en fin de 3ème primaire. Contrairement à ce que nous pourrions penser, les trois groupes d'enfants ne semblent pas se distinguer par leur capacité de mémoire de travail mais par leurs habiletés à traiter les magnitudes numériques symboliques. En 3ème primaire, les faits arithmétiques sont utilisés plus fréquemment par les enfants pour résoudre des problèmes additifs en comparaison aux problèmes soustractifs (Barrouillet et al., 2008).

Une bonne maitrise des faits arithmétiques aura toute son importance lorsque l'enfant sera initié aux procédures de décompositions additives. Dans le cas des additions simples, l'enfant apprend alors à décomposer un des termes du calcul pour retrouver un fait arithmétique connu et faciliter ainsi le traitement du problème. Pour résoudre 4+5, il pourra ainsi s'appuyer sur sa connaissance des doubles pour décomposer le problème comme suit : 4+5 = (4+4) + 1 = 9. Dans le cas où le calcul fait intervenir un passage à la dizaine, le deuxième terme pourra être décomposé de manière à retrouver le complément à 10 : 7+8 = (7+3) +5 = 10+5. Pour se faire, l'enfant doit parfaitement maitriser les décompositions en facteurs premiers du nombre 10.

Lorsqu'il devra traiter des problèmes qui font intervenir des nombres à plusieurs chiffres, l'enfant apprendra à décomposer les termes en dizaines et en unités : 54+13= (50+10) + (4+3) = 60+7= 67. Par la généralisation des deux dernières procédures, il sera en mesure de procéder aux traitements les plus complexes qui lui seront proposés à son âge, soit la résolution de calculs sur des nombres à deux chiffres qui font intervenir un passage à la dizaine : 57+25 = (50+20) + (7+3) +2) = 70+10+2=82.

3.2 Les prédicteurs du développement arithmétique

L'arithmétique est une compétence clef dans le développement mathématique de l'enfant. Une grande partie des enfants qui présentent un retard ou un trouble des apprentissages en mathématiques éprouvent d'ailleurs des difficultés dans ce domaine notamment dans la réalisation des procédures de calcul (Geary et al., 2000) ou encore dans la récupération des faits arithmétiques (Howell et al., 1987). Nombre d'entre eux persévèrent, par ailleurs, longtemps dans l'utilisation de stratégies immatures telles que les procédures de comptage (Geary and al. 1992). Mieux identifier les précurseurs au développement arithmétique est alors un enjeu important pour prévenir les difficultés rencontrées par ces enfants.

Comme bons nombres d'apprentissages, les compétences numériques se développent progressivement durant l'enfance. A la manière d'un château de carte, elles se construisent les unes sur les autres. Ainsi, alors que les enfants semblent éprouver une sensibilité aux quantités dès leur naissance, il faudra attendre l'acquisition du langage oral pour qu'ils apprennent leurs premiers symboles numériques : les mots-nombres. Ils seront alors en mesure d'associer avec précision ces symboles verbaux aux quantités qu'ils représentent, une compétence essentielle à la découverte d'un autre code symbolique : le code arabe. Il faudra alors plusieurs années à l'enfant pour maitriser les règles qui régissent ce nouveau code. La maitrise des codes numériques verbaux et arabe fournissent à l'enfant de bonnes fondations pour aborder les traitements arithmétiques. Dès lors, elles ont fait l'objet d'investigations fréquentes pour déterminer leur valeur prédictive sur le développement arithmétique.

Dans la littérature, deux classes de prédicteurs ont été identifiés : les prédicteurs spécifiques au domaine numérique et les prédicteurs cognitifs généraux. La littérature se référant aux prédicteurs du développement arithmétique est très dense. Aussi, seuls les études se rapportant aux prédicteurs examinés dans les phases expérimentales de cette thèse ont été décrites ici.

3.2.1 Les compétences numériques précoces : Comptage verbal, dénombrement et maitrise de la valeur cardinale des mots-nombres.

Alors que le développement numérique s'ancre profondément dans les connaissances mathématiques acquises en maternelle (Watts et al., 2014), très peu d'études ont été menées pour spécifier le pouvoir prédictif des habiletés numériques précoces (i.e., comptage, dénombrement et cardinalité) sur le développement des compétences arithmétiques des jeunes enfants. En 2021, Lê et Noël ont évalué et suivi des enfants vietnamiens alors scolarisés en 2ème année de maternelle pour tenter de déterminer les meilleurs prédicteurs des compétences arithmétiques deux ans plus tard, soit en fin de 1ère primaire. Sept tâches numériques ont été administrées aux enfants couvrant la comparaison des magnitudes non-symboliques et symboliques (comparaison de collections et de nombres arabes), la connaissance et l'élaboration de la chaine numérique verbale, la maitrise de la valeur cardinale des mots-nombres et l'arithmétique approximative. Les résultats de cette étude ont montré que la connaissance de la chaine numérique verbale et son niveau d'élaboration étaient les prédicteurs les plus importants des compétences arithmétiques, une fois les habiletés cognitives générale contrôlées. Ces résultats ne sont pas surprenants puisque, comme décrit plus haut, les stratégies de calculs utilisées en première primaire s'appuient principalement sur la maitrise du comptage. Ainsi, pour recourir aux stratégies les plus matures (*comptage sur*, 2+3=2 puis 3,4,5 ; *comptage min*, 2+3=3 puis 4,5), l'enfant doit avoir atteint le niveau d'élaboration de la *chaine numérique sécable* et ainsi savoir commencer son comptage à n'importe quel endroit de la chaine et l'arrêter lorsque tous les éléments du second terme ont été ajoutés.

En 2017, Major et al. ont examiné le pouvoir prédictif des compétences d'énumération qui regroupent le subitizing[1] et le dénombrement. Pour ce faire, ils ont proposé à des enfants de 5 ans de résoudre une tâche d'énumération de points qui comprenait entre 1 et 9 cibles. Les mêmes enfants étaient alors évalués une nouvelle fois à l'âge de 6, 8 et 10 ans au cours d'une session dédiée à la résolution de problèmes additifs simples (2+4) ou complexes (33+43). Les résultats de cette recherche ont montré que les compétences d'énumération étaient de bons prédicteurs des compétences arithmétiques à tous les points de mesure. Les enfants les plus lents à réaliser la tâche d'énumération présentaient un rang du sibitizing limité ce qui les obligeait à dénombrer individuellement les points même lorsqu'ils étaient face à des petites collections. Cela révèle, chez ces enfants, une difficulté à extraire des patterns de petites collections, une compétence qui semble fondamentale pour l'apprentissage de l'arithmétique non symbolique (Wilkins et al., 2022).

Enfin, deux études ont examiné la valeur prédictive de la maitrise de la cardinalité sur le développement des compétences arithmétiques. La première a été conduite par Scalise et Ramani (2021) chez des enfants de maternelle, âgés de 3 à 5 ans. Dans cette étude, les auteurs ont proposé aux participants de résoudre des tâches évaluant la maitrise de la valeur cardinale des mots nombres (Combien ?, Donne-moi, montre-moi), la maitrise de la magnitude symbolique (comparaison de nombres arabes) et les compétences dans la résolution de problèmes arithmétiques symboliques. Les enfants ont alors été évalués à 4 mois d'intervalle, durant l'hiver et le printemps de la même année scolaire. Les résultats de cette recherche ont montré que la cardinalité prédisait le développement arithmétique des enfants au travers la maitrise des nombres arabes. En 2018, Chu et al. ont, à leur tour, proposé à des enfants de 3 à 5 ans la tâche « Donne-moi » avant de les retrouver 3 ans plus tard, en 1ère primaire, pour évaluer leurs compétences arithmétiques par la résolution de problèmes symboliques simples (2+4) et complexes (9+15). Les résultats de cette étude ont montré que la maitrise de la valeur cardinale des mots-nombres prédisait non seulement les performances en

[1] Subitizing: capacité à reconnaitre instantanément et sans effort, un groupe d'objets de taille limitée

arithmétiques des jeunes enfants mais également la sophistication des stratégies employées lors de la tâche de calcul. Mis ensemble, ces résultats suggèrent que la compréhension cardinale des symboles numériques est une compétence fondamentale au développement des compétences arithmétiques acquises en début d'enseignement primaire. En effet, sans une totale maitrise de la cardinalité, l'enfant n'est pas en mesure de comprendre les principes qui régissent la *fonction de succession*, qui est, comme nous l'avons vu plus haut, l'un des premiers concepts que l'enfant doit acquérir pour appréhender les notions d'addition et de soustraction (Sarnecka & Carey, 2008; Sella & Lucangeli, 2020). La connaissance de la valeur cardinale des nombres (verbaux ou arabes) sera également nécessaire à l'enfant s'il veut recourir à des procédures de calcul sophistiquées telles que le *comptage min* (2+3=3 puis 4,5) durant laquelle il devra comparer les deux termes de l'opération pour identifier le plus grand.

3.2.2 La connaissance du système positionnel et la base 10

Parce que la résolution de problèmes arithmétiques complexes requière une bonne maitrise du système positionnel et de la base-10, leur valeur prédictive sur le développement des compétences arithmétiques a retenu, ces dernières années, une attention particulière chez certains auteurs. En 2011, Moeller et al. ont proposé à des enfants de 1ère primaire de résoudre deux tâches évaluant leur maitrise du système positionnel (transcodage et comparaison de nombres arabes) avant de les revoir 2 ans plus tard pour une session portant sur l'évaluation des compétences arithmétiques durant laquelle les enfants devaient résoudre des additions impliquant des nombres à deux chiffres (54+23). Les résultats de cette étude ont montré que la maitrise du système positionnel était un précurseur important des compétences arithmétiques de 3ème primaire. Les auteurs ont, par ailleurs, suggéré qu'un déficit précoce de la compréhension du système positionnel pourrait être particulièrement délétère chez les enfants les plus faibles et avoir des conséquences importantes sur l'apprentissage des traitements arithmétiques complexes.

Plus récemment, Laski et al. (2016) ont tenté d'expliquer les processus qui sous-tendent cette relation dans une étude longitudinale. Dans cette recherche, des tâches évaluant la maitrise du système positionnel, la compréhension de la base-10 et les compétences arithmétiques ont été proposées à des enfants alors qu'ils étaient scolarisés en 3ème maternelle puis en 2ème primaire. Les résultats ont prouvé que la maitrise de la base-10 était un prédicteur de développement arithmétique et que cette relation était médiée non seulement par la maitrise du système positionnelle mais également par la maitrise des stratégies de décompositions additives.

Les données de ces deux études confirment donc que la maitrise du système positionnel et de la base-10 sont deux compétences fondamentales au développement des compétences arithmétiques complexes. Cela ne semble pas surprenant puisque, pour résoudre un calcul complexe (ex. 45+24) par des procédures de décomposition des dizaines et des unités (ex. 45+24=(40+20)+(5+4)= 69), l'enfant devra recourir à ses connaissances sur le système positionnel pour identifier les chiffres des unités et des dizaines dans les deux termes de l'addition. Il doit, par ailleurs, faire preuve d'une parfaite maitrise la base-10 de manière à comprendre que le 4 de 45 et le 2 de 24 représentent respectivement 40 et 20 unités.

En somme, tant la une maitrise du code arabe que celle des compétences numériques précoces paraissent comme des prédicteurs numériques importants du développement arithmétique de l'enfant. Outre ces prédicteurs spécifiques au domaine numérique, les traitements arithmétiques requièrent des facteurs cognitifs généraux dont l'importance dans le développement du calcul a été investigué à de multiples reprises.

3.2.3 Un prédicteur cognitif : La mémoire de travail

L'un des prédicteurs cognitifs du développement arithmétique le plus étudié dans la littérature est sans doute la mémoire de travail qui se réfère à la capacité à stocker et à manipuler temporairement des informations nécessaires à la réalisation de tâches cognitives complexes. Très récemment, Zhang et al. (2023) ont publié une méta-analyse pour examiner les liens qui existent entre la mémoire de travail et les performances arithmétiques chez des enfants âgés de 6 à 12 ans et scolarisés en primaire. L'analyse de 46 études regroupant un total de 11 224 participants a montré qu'il existe une corrélation moyenne et significative entre la mémoire de travail et les performances arithmétiques chez ces enfants. La mémoire de travail verbale est la plus fortement corrélée à l'arithmétique en comparaison à la mémoire visuo-spatiale. L'addition et la soustraction (écrite ou verbale) sont les opérations qui sollicitent le plus cette fonction cognitive. La résolution de problèmes complexes impliquant des stratégies de décomposition est particulièrement consommatrice de ressources puisque l'enfant devra s'appuyer sur sa mémoire de travail verbale pour maintenir en mémoire des résultats de calculs intermédiaires.

La mémoire de travail est ainsi une fonction cognitive fondamentale au développement des compétences arithmétiques de l'enfant. Il est d'ailleurs fréquent de relever des capacités réduites en mémoire de travail verbale chez les enfants qui présentent des difficultés ou un trouble des apprentissages en mathématiques (e.g., De Smedt et al., 2013; Mazzocco et al., 2011). En conséquent, face à des tâches numériques à forte charge en mémoire de travail, ces enfants utiliseront plus souvent un support concret tels que leurs doigts pour représenter les quantités impliquées dans les problèmes et ainsi diminuer la charge cognitive de la tâche en cours (Noël, 2005, 2009; Passolunghi & Cornoldi, 2008). En 2015, Crollen et Noël. ont illustré ce phénomène en soumettant des enfants de 5 ans à deux tâches expérimentales. La première consistait à compter le nombre de fois où un son particulier, par exemple la sonnerie d'un téléphone, apparaissait parmi une liste de distracteurs auditifs. Dans la seconde tâche, les enfants devaient repérer non plus une mais deux cibles différentes parmi une liste de distracteurs. Les enfants devaient résoudre les deux tâches dans trois conditions : une condition libre, une condition pendant laquelle ils devaient presser deux balles en mousse empêchant le recours aux doigts et une condition dans laquelle les enfants devaient presser la balle en mousse avec le pied. Les résultats de cette étude ont montré une baisse significative des performances des enfants dans la deuxième tâche lorsque l'utilisation des doigts était neutralisée par la pression des balles en mousse. Privés de leurs doigts, les enfants n'étaient ainsi plus en mesure d'utiliser ce support concret pour réduire la charge en mémoire de travail de la tâche proposée entrainant, en conséquent, une chute de leurs performances.

Synthèse du Chapitre 1

Le développement numérique est un processus lent qui s'amorce dès les premiers mois de vie. A cet âge, les traitements numériques réalisés par l'enfant sont approximatifs et limités aux petites quantités.

Vers 2 ans, les traitements numériques deviennent plus précis puisque l'enfant acquière ses premières compétences langagières. Les mots-nombres sont alors employés quotidiennement. Dès son entrée à l'école, l'enfant apprend à les réciter dans un ordre précis pour former la chaine numérique verbale. L'apprentissage de cette chaine se fait au travers de deux phases développementales : la phase d'acquisition et la phase d'élaboration. Une bonne maitrise de la chaine numérique verbale est essentielle pour que l'enfant puisse réaliser les activités de dénombrement. Vers 3 ans, un enfant peut être en mesure de dénombrer une collection sans pour autant comprendre que le dernier mot-nombre énoncé se rapporte à l'ensemble des éléments de la collection. La maitrise de la valeur cardinale des mots-nombres se développe lentement, entre 3 et 6 ans, par paliers successifs.

Vers 5 ans, l'enfant aborde un nouveau code symbolique : le code arabe. Il apprend alors les règles lexicales et syntaxiques qui régissent ce code. Il devra, par ailleurs, comprendre que les chiffres prennent une valeur différente selon la place qu'ils occupent dans le nombre.

Vers 6 ans, l'enfant réalise ses premiers calculs. Il utilise d'abord des stratégies de calculs basées sur le comptage. Il apprendra, par la suite, des procédures plus sophistiquées telles que la récupération des faits arithmétiques et les procédures de décomposition additive. Le développement des compétences arithmétiques s'ancre profondément dans la maitrise des compétences numériques précoces (comptage, dénombrement, cardinalité) et du code arabe. Outre les facteurs numériques, les traitements arithmétiques requièrent des facteurs cognitifs généraux tels que la mémoire de travail. Lorsque celle-ci fait défaut, les enfants utilisent des supports concrets tels que les doigts pour représenter les quantités impliquées dans le calcul, diminuant ainsi la charge cognitive de la tâche arithmétique traitée.

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Chapitre 2 – Le rôle des doigts dans l'acquisition des symboles numériques verbaux

Les concepts numériques sont, par définition, profondément abstraits. Le recours à des supports concrets est donc souvent recommandé auprès des enfants pour soutenir leurs apprentissages (Carbonneau et al., 2013). Parce qu'ils sont toujours accessibles et simples à manipuler (Domahs et al., 2008; Soylu et al., 2018), les doigts sont utilisés par les enfants très tôt dans le développement, parfois même avant que les symboles numériques ne fassent sens (Gunderson et al., 2015). A ce jour, de plus en plus de recherches sont menées pour tenter de comprendre comment les doigts contribuent à l'apprentissage des premiers symboles numériques. A partir des travaux menés par Krajewski et Schneider (2009), Roesch et Moeller ont proposé, en 2015, un modèle développemental synthétisant une partie de ces recherches. D'après ce modèle, les doigts interviennent à trois stades distincts du développement numérique précoce. Au premier stade (Niveau 1 : Compétences numériques de base), les doigts contribuent à l'acquisition de la chaine numérique verbale. A un stade de développement plus avancé (Niveau 2 : Concept nombre-quantité), ils soutiennent l'enfant dans l'acquisition de la valeur cardinale des mots-nombres. Enfin, au niveau le plus avancé (Niveau 3 : Relations numériques), les doigts sont un support à l'apprentissage des premières compétences arithmétiques. Dans le présent chapitre, les évidences concernant les deux premiers niveaux du modèle développemental de Roesch et Moeller (2015) seront synthétisées, complétées et actualisées. La synthèse des études relatives à la contribution des doigts au développement de l'arithmétiques (Niveau 3) fait l'objet de la synthèse méthodique présentée dans le Chapitre 3.

1 Doigts et apprentissage des compétences numériques de base : comptage et dénombrement

A partir de 3 ans, l'enfant apprend à énoncer la chaine numérique verbale correctement et à utiliser cette séquence numérique dans des activités de dénombrement. A ce stade, le développement des compétences numériques est particulièrement ancré dans les expériences sensorimotrices de l'enfant (Asakawa & Sugimura, 2022; Barnes et al., 2005; Fischer et al., 2018). Les doigts peuvent alors être utilisés pour accompagner la récitation de la chaine verbale dans une gestuelle parfois apprise sans aucune instruction formelle (Morrissey et al., 2016; Previtali et al., 2011) et répondant à des codes culturels (Bender & Beller, 2011). En Belgique, les doigts sont ainsi levés séquentiellement, en commençant par le pouce de la main dominante alors associé au mot-nombre "un" suivi de l'index, du majeur et de l'annulaire pour terminer par l'auriculaire. Au besoin le comptage pourra se poursuivre par le pouce de la main non-dominante jusqu'à ce que l'auriculaire de la même main soit levé (Figure 3; Bender & Beller, 2012; Berteletti & Booth, 2016; Hohol et al., 2018).

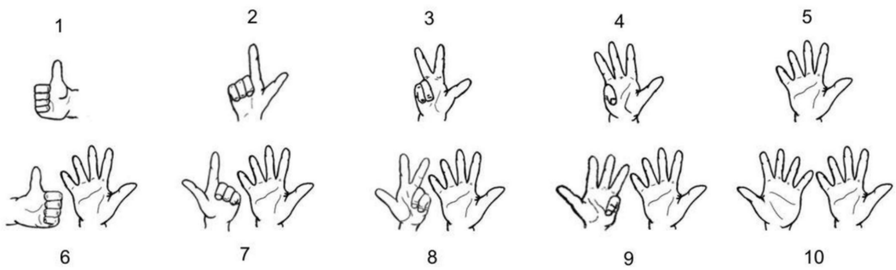

Figure 2 : Système de comptage sur les doigts observé chez les européens (issue de Domahs et al. 2012)

Comme ces routines de comptage sur les doigts sont présentes dans les activités quotidiennes de l'enfant, certains auteurs ont suggéré qu'elles puissent soutenir le développement des premières connaissances conceptuelles telles que les principes de dénombrement (Gelman & Gallistel, 1978). Ainsi, l'association d'un mot-nombre avec un doigt levé pourrait supporter la familiarisation de l'enfant avec le principe de *correspondance terme-à-terme*. Cette mise en correspondance pourrait aider l'enfant à percevoir chaque mot-nombre de la chaine numérique verbale comme une entité distincte (Bender & Beller, 2011), contribuant à l'élaboration de la chaine verbale. Du niveau d'élaboration le plus élémentaire (*niveau chapelet*), l'enfant évoluerait vers un stade de développement plus avancé (*niveau de la chaine sécable*). Par ailleurs, le recours aux doigts dans les activités de comptage pourrait soutenir l'enfant dans sa compréhension du *principe de l'ordre stable et conventionnel* puisque le comptage sur les doigts implique des séquences motrices aussi stables que la chaine numérique verbale (Crollen et al., 2011; Roesch & Moeller, 2015). A titre d'exemple, cette pratique pourrait aider l'enfant à comprendre que le mot-nombre "deux", associé à l'index, vient juste après le mot-nombre "un" associé au pouce, levé juste avant l'index. Il conviendra toutefois de noter que, à notre connaissance, ces suggestions n'ont jamais été testées expérimentalement ce qui limite actuellement la compréhension de ces phénomènes et de leurs mécanismes.

A ce stade de développement, les doigts sont également sollicités dans la mise en œuvre des procédures de dénombrement. L'enfant doit alors mettre en correspondance les objets pointés d'une collection avec les mots-nombres de la chaine verbale. Entre 3 et 5 ans, le recours au pointage permet à l'enfant d'améliorer ses performances dans ce type de tâche (Gelman & Meck, 1983). A ce titre, lorsqu'il est proposé à des enfants de 4 ans de dénombrer des collections sans pointer les éléments avec leurs doigts, une chute importante des performances est observée en comparaison à la condition contrôle durant laquelle le pointage était autorisé (Saxe & Kaplan, 1981).

Pour expliquer pourquoi et comment le pointage contribue à l'apprentissage du dénombrement, Alibali et DiRusso (1999) ont proposé à des enfants de 4 ans de dénombrer des collections contenant entre 7 et 17 objets au cours d'une recherche menée en 2 volets. Lors de la première session d'évaluation les enfants devaient résoudre la tâche dans trois conditions expérimentales : (1) Une condition libre durant laquelle aucune procédure n'était suggérée à l'enfant, (2) une condition facilitatrice durant laquelle le recours au pointage était explicitement recommandé et (3) une condition limitante durant laquelle le pointage était interdit. Les résultats obtenus lors de cette première phase expérimentale ont montré que les performances des enfants chutaient lorsque le geste de pointage était interdit. Les enfants commettaient alors beaucoup plus d'erreurs d'omission de cibles ou de double pointage. Les auteurs ont donc suggéré que, chez les jeunes enfants, le pointage permettrait de marquer chaque objet compté pour en garder une trace en mémoire. Le recours au pointage permettrait ainsi à l'enfant de distinguer les objets qui ont déjà été comptés, des objets qu'il reste à compter. Lors de la seconde phase expérimentale, les participants étaient soumis à la même tâche dans deux conditions différentes : (1) une condition active durant laquelle les enfants devaient dénombrer eux-mêmes les objets, (2) une condition passive durant laquelle ils devaient compter verbalement pendant qu'une poupée pointait les objets de la collection. Les résultats obtenus lors de cette phase expérimentale ont montré que les enfants étaient plus précis lorsqu'ils procédaient eux-mêmes au pointage des objets que lorsque le pointage était réalisé par un tiers. Lorsque le pointage était opéré par la poupée, les enfants produisaient d'avantage d'erreurs de coordination (e.g., deux mots-nombre énoncé alors qu'un seul objet a été pointé). Le recours au pointage dans une tâche de dénombrement ne supporterait donc pas uniquement le marquage des objets de la collection mais aiderait également les enfants à coordonner le geste de pointage avec la récitation des mots-nombres.

A partir de 6 ans, les enfants se détachent progressivement de la procédure de pointage digital pour commencer à utiliser le pointage visuel (Saxe & Kaplan, 1981). Les gestes de pointage restent toutefois imprécis chez les enfants qui présentent des troubles moteurs. A cet âge, les enfants avec infirmité motrice cérébrale produisent plus d'erreurs de pointage dans une tâche de dénombrement que leurs pairs au développement typique, notamment lorsque les éléments de la collection sont disposés aléatoirement sur la feuille (Camos et al., 1998). A 8 ans la procédure est totalement automatisée. Soumis à une tâche de dénombrement, rares sont les enfants qui produisent encore des erreurs de pointage (Camos et al., 2001).

2 Doigts et acquisition de la valeur cardinale des mots-nombres

Entre 3 et 6 ans, l'enfant acquière la maitrise de la valeur cardinale des mots-nombres. Il est alors en mesure de comprendre que le dernier mot-nombre énoncé dans une tâche de dénombrement se réfère à l'ensemble des objets de la collection traitée et pas uniquement au dernier élément compté (Gelman & Gallistel, 1978). Le mot-nombre devient alors un symbole numérique utilisé pour représenter une quantité (Wiese, 2007). Il faudra plusieurs années à l'enfant pour parvenir à associer ces symboles verbaux aux quantités qu'ils représentent (Sarnecka & Carey, 2008). La maitrise de cette compétence est une étape fondamentale dans le développement numérique. Plus tôt l'enfant de maternelle maitrisera ces associations, meilleures seront ses compétences numériques à son entrée à l'école primaire (Geary et al., 2018).

Dans son quotidien, l'enfant est susceptible d'utiliser ses doigts pour représenter le cardinal associé à un mot-nombre. Ainsi, il n'est pas rare de voir un enfant de trois ans lever le pouce, l'index et le majeur simultanément pour communiquer son âge. Certains travaux menés chez des enfants d'âge scolaire ou chez des jeunes adultes suggèrent que ces gestes faciliteraient l'entrée dans la cardinalité (Di Luca & Pesenti, 2011; Krinzinger, 2011). En 2008, Di Luca et Pesenti ont mené une recherche en 2 volets auprès de jeunes adultes belges francophones pour montrer le statut particulier de ces gestes. Lors de la première phase expérimentale, des photos représentant des gestes numériques à valeur cardinale étaient présentées aux participants. Les gestes étaient soit canoniques (i.e., conformes aux habitudes de comptage d'un adulte européen ; e.g., pouce, index et majeur levés pour représenter 3), soit non canoniques (e.g., pouce, majeur et annulaire levés pour représenter 3). Les volontaires devaient nommer le cardinal représenté par chaque geste, le plus rapidement possible et sans commettre d'erreur. Les résultats de cette première expérience montrent que les représentations canoniques sont identifiées plus rapidement et plus précisément chez les jeunes adultes que les représentations non canoniques. Les auteurs suggèrent alors que, lorsqu'elles sont conformes aux habitudes de comptage et donc connues des participants depuis leur enfance, les représentations canoniques sont stockées en mémoire à long terme. Dans la seconde phase expérimentale, les participants devaient réaliser une tâche de comparaison numérique symbolique (e.g., plus petit ou plus grand que 5) dans laquelle les nombres arabes traités étaient amorcés par des gestes numériques canoniques ou non-canoniques. Les résultats ont montré que les participants étaient plus rapides et plus précis dans la tâche de comparaison numérique lorsque les nombres arabes étaient amorcés par des représentations canoniques en comparaison aux représentations non-canoniques des gestes-nombres. L'identification rapide des représentations canoniques tiendrait donc davantage à leur valeur sémantique qu'à une préférence visuelle. En effet, lorsqu'elles sont traitées, les représentations canoniques fournissent un accès direct à la sémantique du nombre ce qui facilite les traitements numériques. A ce titre, ces représentations jouissent donc d'un statut symbolique. Dans leur discussion, les auteurs soulignent que ces représentations disposent également d'un statut iconique. En effet, lorsqu'il produit un geste numérique pour représenter le cardinal d'une collection, l'enfant lève exactement le même nombre de doigts qu'il y a d'éléments dans la collection (Wiese, 2003). Bénéficiant ainsi d'un double statut symbolique et iconique (Figure 3), Di Luca et Pesenti (2008) proposent que les représentations canoniques véhiculées par les doigts pourraient permettre aux jeunes enfants de créer des ponts entre les symboles verbaux et les quantités qu'ils représentent, facilitant ainsi l'apprentissage de la valeur cardinale des mots-nombres.

Suite à cette recherche, Nicoladis et al. ont investigué, en 2018, les origines développementales de la sensibilité à l'iconicité chez des enfants de 2 à 5 ans afin de savoir si elle est présente tôt dans le développement, ce qui faciliterait l'apprentissage des gestes numériques, ou si elle n'apparait que tardivement. Dans ce dernier cas, les gestes numériques seraient appris par les enfants comme tout autre symbole numérique arbitraire (i.e., mots-nombres). Pour ce faire, les auteurs ont proposé aux enfants de réaliser la tâche « Donne-moi » (Wynn, 1990; cf. chapitre 1) dans deux modalités différentes : (1) une modalité verbale impliquant le traitement ou la production de mots-nombres (e.g., « Donne-moi trois jouets »), (2) une modalité digitale impliquant le traitement des gestes numériques (i.e., « Donne-moi « ça » de jouets » ; L'expérimentateur montre « trois » en levant le pouce, l'index et le majeur). La modalité digitale a été répétée dans deux conditions : (1) une condition canonique durant laquelle les gestes-nombres produits par les expérimentateurs étaient conforment aux habitudes de comptage des enfants et (2) une condition non canonique impliquant des gestes-nombres non conventionnels. Les résultats de cette étude ont montré que les enfants traitaient mieux les représentations canoniques que les représentations non canoniques, quel que soit leur âge. Il n'y aurait donc aucune preuve que les jeunes enfants de 2 et 3 ans soient plus sensibles au statut iconique des gestes numériques. Les gestes-nombres seraient alors appris comme des symboles à part entière.

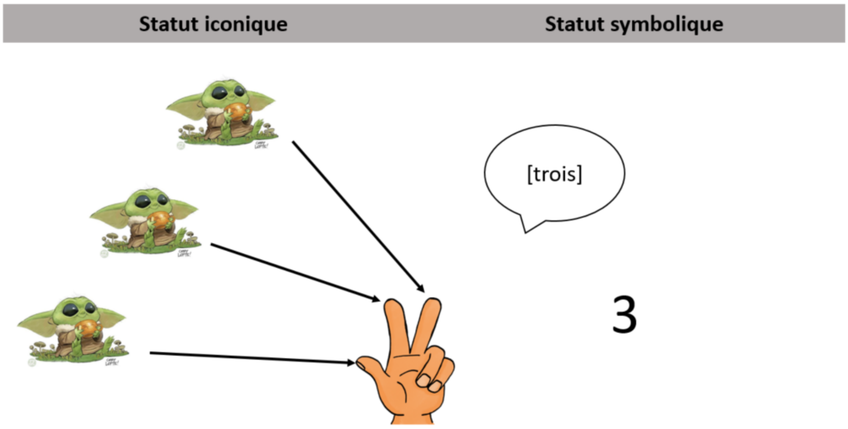

Figure 3 : Double statut iconique et symbolique des gestes-nombres.

A l'heure actuelle, très peu de travaux ont été menés pour comprendre comment les gestes numériques contribuent au développement numérique des jeunes enfants. En 2010, Nicoladis et al. proposent l'hypothèse selon laquelle le statut iconique des gestes-nombres faciliterait les traitements numériques des enfants âgés de 3 à 5 ans. Ainsi, les enfants comprendraient et utiliseraient plus facilement des représentations symboliques iconiques (gestes numériques) en comparaison aux représentations symboliques arbitraires (mots-nombres) pour traiter les quantités. Pour tester cette hypothèse, les tâches « Donne-moi » et « Combien » (Wynn, 1990; cf. chapitre 1) ont été présentées aux participants dans les modalités verbales et digitales telles que présentées plus haut. Les résultats de cette recherche montrent que les enfants étaient plus précis lorsqu'il s'agissait d'associer les quantités avec des mots-nombres plutôt qu'avec des gestes nombres. Rejetant ainsi leur hypothèse, les auteurs suggèrent que les jeunes enfants ne bénéficieraient pas du statut iconique des gestes numériques pour associer les quantités aux symboles numériques verbaux. Ces gestes numériques seraient alors utilisés par convention culturelle. Les enfants imiteraient les adultes pour participer aux interactions sociales sans pour autant que le recours à ces représentations contribue à l'apprentissage des mots-nombres.

Ces propositions ne font toutefois pas l'unanimité dans la communauté scientifique. En 2015, Gunderson et al. ont ainsi remis en question des conclusions de Nicoladis et al. (2010) en arguant que les résultats obtenus en faveur des mots-nombres étaient plus robustes chez les enfants les plus âgés de l'échantillon (4-5 ans) en comparaison aux plus jeunes (2-3 ans). Pour Gunderson et al. (2015), cela reflète que les enfants âgés maitrisaient déjà la valeur cardinale des mots-nombres avant l'expérimentation. Ces enfants utilisaient alors davantage les mots-nombres que les gestes numériques dans leurs activités quotidiennes ce qui explique pourquoi ils étaient plus précis pour traiter les symboles verbaux que les symboles digitaux. Pour savoir si les gestes numériques contribuent au développement de la valeur cardinale des mots-nombres, les auteurs proposent donc de travailler avec des enfants qui n'ont pas totalement acquis le principe de cardinalité.

Dans leurs travaux, Gunderson et al. (2015) ont donc cherché à déterminer si l'utilisation des gestes numériques précédait celle des mots-nombres chez ces enfants. Pour se faire, ils ont présenté aux participants des cartes sur lesquelles des collections d'objets de tailles différentes (de 1 à 10) étaient dessinées. Les enfants étaient alors invités à communiquer le nombre d'images qu'ils voyaient soit avec des gestes numériques, soit avec des mots-nombres. Le niveau cardinal de chaque enfant était évalué par la tâche « Donne-moi » en modalité verbale. Les résultats de cette étude montrent que les enfants qui ne maitrisaient pas encore le principe de cardinalité étaient plus précis pour communiquer les quantités à partir des gestes numériques en comparaison au mots-nombres, particulièrement lorsque la taille des collections traitée était supérieure à leur niveau de développement cardinal. Pour prouver l'apport des gestes numériques au développement de la compréhension cardinale des mots-nombres, Orrantia et al. (2022) ont mené un essai randomisé contrôlé auprès d'enfants âgés de 3 ans. L'intervention était conçue à partir d'activités classiquement utilisées à l'école maternelle pour enseigner le principe de cardinalité (i.e., chanson numérique, dénombrement de collections impliquant différents supports concrets). Les enfants étaient alors répartis aléatoirement dans deux groupes d'entrainement. Dans le premier groupe (contrôle), l'enseignant était invité à n'utiliser que des mots-nombres pour représenter les quantités. Les activités proposées aux enfants du second groupe (expérimental) étaient strictement comparables à celles proposées aux enfants du groupe contrôle à la différence près que les mots-nombres étaient systématiquement associés à des gestes numériques. En fin d'intervention, les enfants du groupe expérimental présentaient de meilleures performances que les enfants du groupe contrôle, prouvant l'existence d'un lien causal entre l'utilisation des gestes numériques et l'apprentissage de nouveaux mots-nombres chez les jeunes enfants. En somme, le rôle des doigts dans l'acquisition et le développement de la valeur cardinale des mots-nombres fait l'objet encore aujourd'hui l'objet d'un débat dans la communauté scientifique. Si les gestes numériques semblent faciliter l'apprentissage de la cardinalité, d'autres recherches sont encore nécessaires pour comprendre les mécanismes qui sous-tendent cet apprentissage.

Synthèse du Chapitre 2

Parce qu'ils sont toujours accessibles et simples à manipuler, les doigts sont souvent utilisés par les enfants pour résoudre des problèmes numériques. A partir de 3 ans, Ils peuvent être utilisés pour accompagner la récitation de la chaine numérique verbale dans une gestuelle répondant à des codes culturels. Ces gestes pourraient soutenir le développement des principes de dénombrement (*correspondance terme-à-terme* et *principe d'ordre stable et conventionnel*) et contribuer à l'élaboration de la chaine numérique verbale.

Les doigts sont fortement sollicités dans la mise en œuvre des procédures de dénombrement durant lesquelles l'enfant doit mettre en correspondance chaque objet pointé avec un mot-nombre de la chaine numérique verbale. Entre 3 et 5 ans, le recours au pointage dans les activités de dénombrement aide l'enfant à marquer les objets déjà comptés et à coordonner le geste à la parole.

Dans son quotidien, l'enfant utilise également ses doigts pour représenter le cardinal associé à un mot-nombre. Certains travaux suggèrent que le recours à ces gestes numériques faciliteraient l'apprentissage de la valeur cardinale des mots-nombres. Puisqu'ils disposent d'un double statut iconique et symbolique, ces gestes pourraient permettre aux jeunes enfants de créer des ponts entre les symboles verbaux et les quantités qu'ils représentent. Cette proposition ne fait toutefois pas l'unanimité dans la communauté scientifique. Pour certains auteurs, les gestes numériques seraient utilisés par les enfants pour participer aux interactions sociales sans pour autant que le recours à ces représentations contribue à l'apprentissage de la valeur cardinale des mots-nombres.

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Chapter 3 - Finger Use and Arithmetic Skills in Children and Adolescents: A Scoping Review

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REVIEW ARTICLE

Abstract

Although the role played by finger use in children's numerical development has been widely investigated, their benefit in arithmetical contexts is still debated today. This scoping review aimed to systematically identify and summarize all studies that have investigated the relation between fingers and arithmetic skills in children. An extensive search on Ovid PsycINFO and Ovid Eric was performed. The reference lists of included articles were also searched for relevant articles. Two reviewers engaged in study selection and data extraction independently, based on the eligibility criteria. Discrepancies were resolved through discussion. Of the 4,707 identified studies, 68 met the inclusion criteria and 7 additional papers were added from the reference lists of included studies. A total of 75 studies were included in this review. They came from two main research areas and were conducted with different aims and methods. Studies published in the mathematical education field (*n*=29) aimed to determine what finger strategies are used during development and how they support computation skills. Studies published in cognitive psychology and neuroscience (*n*=45) specified the cognitive processes and neurobiological mechanisms underlying the fingers/arithmetic relation. Only one study combined issues raised in both research areas. More studies are needed to determine which finger strategy is the most effective, how finger sensorimotor skills mediate the finger strategies/arithmetic relation and how they should be integrated into educational practice.

Keywords

Finger use, arithmetic, mathematical education, cognitive development and neuroscience, scoping review.

1 Introduction

All over the world, children use their fingers to perform numerical processing. This recurrent use leads to the emergence of habits of counting on fingers that persist into adulthood (Hohol et al., 2018) and are embedded in local cultural practices (Bender & Beller, 2011; Lindemann et al., 2011). For example, European people raise each finger, one at a time, starting with the thumb and moving to the second hand to represent the numbers 1 to 10, whereas Chinese people prefer to start counting with their index finger and represent the numbers 1 to 9 with the same hand (Bender & Beller, 2012; Domahs et al., 2010). Fingers are commonly used in various mathematical contexts because they constitute a tool that is always available and easy to manipulate (Domahs et al., 2008). Fingers also have the advantage of being a multisensory representation of the quantity (i.e., tactile and visual) (Domahs et al., 2008; Soylu et al., 2018) and providing an embodied representation of ordinal and cardinal information conveyed by numbers (Wasner et al., 2015). For instance, representing quantities with fingers helps children to solve arithmetic problems (Björklund et al., 2019; Kullberg & Björklund, 2020) while tracing with the index finger over the surface of figures enhances geometry and spatial reasoning (Ginns et al., 2016) and facilitates transfer to new problems (Ginns et al., 2020).

The role played by finger counting in the development of children's numerical and arithmetic skills has been explored in two main research areas: (1) mathematics education, and (2) cognitive psychology and neuroscience. The findings in these two research fields are often contradictory, and the place of fingers in mathematics education is still currently a matter of debate. In their narrative review, Moeller et al. (2011) state that educators recommend abandoning fingers in favor of abstract mental representations, whereas cognitive psychologists generally agree that fingers have a beneficial influence on children's numerical development. On closer inspection, however, it would seem that data for and against the use of fingers in numerical and arithmetic activities come as much from mathematics education as from cognitive psychology and neuroscience. Over the last two decades, a great deal of evidence from both fields has fueled this debate.

Some of this evidence questions the benefit of finger use in children's numerical and arithmetic development. Interviews conducted with parents and educators show that many elementary school teachers prohibit finger-based strategies for calculating in class to promote the usage of mental strategies, arguing that finger-based strategies are unnecessary and should only be used by preschoolers (Boaler & Chen, 2017; Multu et al., 2020). Supporting this belief, there is behavioral evidence that questions the benefit of finger use. While some studies in the past have shown that finger sensorimotor skills such as finger gnosia are correlated with children's arithmetic skills (Costa et al., 2011; Noël, 2005), recent findings show conflicting results (Long et al., 2016; Malone et al., 2020; Newman, 2016). Moreover, recent specific training of finger recognition skills did not provide evidence of their predictive value for the development of computation skills (Schild et al., 2020, but see Gracia-Bafalluy & Noël, 2008, for contradictory results). For preschoolers, finger number gestures (e.g., number 3 shown by raising thumb, index and middle finger) have been shown to be initially learned as arbitrary symbols (Nicoladis et al., 2018), and the understanding of these number gestures was found to be less advanced than that of number words (Nicoladis et al., 2010).

Consequently, some authors recommend introducing mathematical concepts in school primarily through the abstract number word sequence rather than with manipulatives (Johansson, 2005) such as tokens or fingers, since teaching mathematical concepts with these manipulatives does not predict the children's numerical development (Morgan et al., 2015). Therefore, some common classroom teaching practices, such as the Cover, Copy and Compare program, promote learning computation through memory-based strategies at the expense of finger-based strategies (Skinner et al., 1989; for a review, see Stocker & Kubina, 2017). Moreover, some programs that openly discourage children from using their fingers to calculate in the early stage of learning arithmetic have been found to be more effective than traditional instructions (McKenna et al., 2005).

By contrast, many behavioral and neuroanatomical studies have indicated that fingers influence both children's and adults' numerical processing. Regarding behavioral evidence in adults, the structure of the Western finger counting system (i.e., successively raising each finger of the first hand before switching to the second hand) has been shown to influence number magnitude processing (Domahs et al., 2010; Morrissey et al., 2016) and mental computation (e.g., increasing split-five errors) (Domahs et al., 2008; Klein et al., 2011). When finger number gestures are canonical (i.e., consistent with counting habits, such as three shown by raising thumb, index and middle finger), their processing provides automatic access to number magnitude (Di Luca et al., 2010; Di Luca & Pesenti, 2008; Sixtus et al., 2017) and facilitates arithmetic problem solving (Badets et al., 2010; Barrocas et al., 2019; van den Berg et al., 2021). Similarly, passive (Imbo et al., 2011) or active (Michaux et al., 2013; but see Morrissey et al., 2020) motor interference disrupts problem solving, suggesting that, even in adults, fingers play a functional role in numerical contexts. This behavioral evidence is further supported by several neuroanatomical studies. The first data were described in adults with Gerstmann syndrome, in which brain lesions at the intraparietal sulcus result in a conjunction of four key symptoms: finger agnosia, acalculia, right-left disorientation and agraphia (Gerstmann, 1940; Mayer et al., 1999). Since then, studies using brain imaging techniques (Andres et al., 2012; Soylu & Newman, 2016; Tschentscher et al., 2012) and transcranial magnetic stimulation (Andres et al., 2007; Rusconi et al., 2005; Sato et al., 2007) have confirmed the existence of common cerebral correlates supporting both finger abilities and numerical skills. All this evidence suggests that adults have internalized finger-based numeration learned in childhood during their early school years.

In 2015, Roesch and Moeller proposed a developmental model in an attempt to clarify the contribution of fingers at different stages of children's numerical development. At the first developmental stage, when children learn the sequence of number words, fingers support the segmentation of this sequence by the association of each raised finger with a specific number word (Beller & Bender, 2011). In addition, fingers are involved in procedural counting, tagging each item counted and keeping track of those that have already been counted (Alibali & DiRusso, 1999; Graham, 1999). Procedural counting influences the learning of early conceptual knowledge (Fischer et al., 2018), such as cardinality. At the second developmental stage, when children learn the cardinal principal, number gestures can be used to communicate the cardinal of a set and learn the cardinal value of new number words (Gibson et al., 2019; Gunderson et al., 2015; but see Nicoladis et al., 2018; Nicoladis et al., 2010). Lastly, at the third developmental stage, when children start to calculate, they draw on their counting and cardinal skills to acquire their first arithmetic skills and solve problems, mobilizing fingers as an external support (Roesch & Moeller, 2015).

While a hot topic at all stages of numerical development, the benefit of finger use is mainly debated for arithmetic development. A focused summary of all the existing evidence about the specific contribution of finger use to arithmetic development in children is necessary, to provide a clearer picture of the current state of the field. To date, the five narrative reviews which have attempted to overview the evidence about the relationship between finger-use and numerical cognition suggest that various finger skills support numerical and arithmetic abilities (Barrocas et al., 2020; Berteletti & Booth, 2016; Kaufmann, 2008; Moeller et al., 2011; Soylu et al., 2018). However, two of them are dated and need to be updated with the findings of the last decade (Kaufmann, 2008; Moeller et al., 2011). Additionally, the majority of these narrative reviews addressed broader questions, beyond the scope of children's arithmetic development, or limited their report to typically developing children. In fact, all these reviews reported evidence across all numerical domains with no specific focus on arithmetics (where the role of fingers is most debated). Yet, while the influence of finger use is probably different as a function of numerical tasks, knowledge is predominantly lacking regarding the nature of the finger skills specifically involved in arithmetic development. As a related issue, none of the current narrative reviews specifically targeted the whole population of school-aged children, who are likely to use their fingers during arithmetic activities. Four of them reported evidence from children and adults (Berteletti & Booth, 2016; Kaufmann, 2008; Moeller et al., 2011; Soylu et al., 2018) and one focused on kindergartners (Barrocas et al., 2020). Moreover, only evidence from typically developing participants (Barrocas et al., 2020; Berteletti & Booth, 2016; Moeller et al., 2011;

Soylu et al., 2018) or from participants with mathematical learning disabilities (Kaufmann, 2008) has been reported without addressing the full range of atypical development. Yet, there is still a considerable amount of work to be done to determine the best time window, and the profiles of children sensitive to finger use in arithmetic development.

There are also limitations in the reviews that have already been published. One limit concerns the terminology used as four of the current narrative reviews use the term “finger-use” without clarifying what specific concepts are encompassed by this term (Berteletti & Booth, 2016; Kaufmann, 2008; Moeller et al., 2011; Soylu et al., 2018). The latest review (Barrocas et al., 2020) has brought significant progress to the field by disclosing the terminological disagreement among researchers and defining the concepts underlying sensorimotor skills. The writers have provided interesting leads to refine the search around fine motor skills of relevance for numerical development, including focusing on the purest measures of fine motor skills (without tools, limited executive function and visuo-spatial processing). A second limit concerns the methodology of these narrative reviews as they do not follow any systematic process to identify, characterize and summarize evidence. Their study reports are possibly driven by the authors’ knowledge and, thus, based on statements made in the restricted number of identified studies. As a result, some relevant data could have been dismissed or involuntarily ignored, leaving the door open for reported biases.

To sum up, although the existing narrative reviews provide important information about finger use in a mathematical context, there is currently no compelling focused synthesis of all existing evidence on the specific contribution of finger use to arithmetic development in typically, and atypically, developing children. Therefore, the current work presents a scoping review to fill this gap and to provide a robust synthesis of the evidence on this topic. This study design warrants the identification of evidence in a transparent and objective manner in order to counteract the selection biases present in current narrative syntheses. Furthermore, this scoping review prepares the ground for a systematic review, since it ensures that there is sufficient relevant evidence on a given question to start this work. The main objective of this scoping review is to identify, characterize and summarize all qualitative and quantitative evidence from the fields of mathematical education and cognitive psychology that has investigated the relationship between finger use and arithmetic skills in school-aged children and adolescents, with typical, or atypical, development.

2 Methods

2.1 Protocol and Registration

The research protocol was registered on May 25, 2021, in the Open Science Framework (OSF), see [https://osf.io/ek2gd/?view_only=c23029cdaae2437abeeaa5a3be93a32b]. This review followed the recommendations suggested in the JBI methodology for scoping reviews (Aromataris & Munn, 2020) and was reported in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-analysis extension for Scoping Reviews (PRISMA-ScR) Checklist (Tricco et al., 2018).

2.2 Eligibility Criteria

The Participants, Concept, Context (PCC) eligibility criteria (Aromataris & Munn, 2020) are described in the following sections.

2.2.1 Population

Studies including children or adolescents aged between 3 and 17 years enrolled in either regular or special education systems were eligible for this review. Children with typical and atypical development were included. Atypical development entailed, here, the presence of a neurodevelopmental disorder resulting from unknown origin, as in many occurrences of learning disabilities (e.g., developmental language disorder, developmental coordination disorder, mathematics learning disorder) or from a non-progressive congenital pathology detected at birth or in the first months of life (e.g., genetic syndrome, cerebral palsy). Conversely, studies conducted of participants with acquired injuries (e.g., traumatic brain injury, neuroblastoma) or progressive neurological conditions (e.g., epilepsy) were excluded.

2.2.2 Concept

The concept examined in this scoping review was *the use of fingers*. Only studies involving a task requiring participants to use their fingers physically and assessing finger skills with no contamination by other irrelevant cognitive abilities were included (e.g., visuospatial processing, visual guidance, see Barrocas et al., 2020 for a discussion). This criterion resulted in two main types of measures, assessing either the utilization of *finger-based strategies* during calculation, both qualitatively (i.e., how are fingers used) and quantitatively (i.e., how frequently they are used), or *finger sensorimotor skills* (e.g., ability to perceive sensory input and to execute fine motor movements whith the fingers). Regarding *finger-based strategies*, only studies targeting motor outcomes (e.g., number of occurrences of finger-based strategies during problem solving; finger movement analysis during calculation) were included. Taking these criteria into account, studies focusing on the observance of finger movements performed by a third party (e.g., influence of teacher's finger movements on children's arithmetic performance) were excluded. With regard to *finger sensorimotor skills*, studies targeting graphomotor and writing skills were not deemed eligible because fine motor skills involving fingers were entangled with other cognitive abilities such as pencil manipulation or letter/word knowledge (Barrocas et al., 2020; Carlson et al., 2013; Suggate et al., 2018).

2.2.3 Context

This review is limited to studies examining finger use in the context of *arithmetic problem solving*. Only studies requiring participants to solve arithmetic problems on their own were selected. Arithmetic problems included single- or multi-digit problems of any type (i.e., addition, subtraction, multiplication, division) in any form (e.g., mental computation with or without time constraints, written computation, arithmetic verification task). Furthermore, studies assessing mathematical skills using a test battery were included only if and when arithmetic measures could be clearly identified and isolated from the other mathematical scores. Studies asking participants to solve other types of mathematical tasks (e.g., geometry, etc.) were excluded.

2.2.4 Types of Sources

Only peer-reviewed journal articles written in English, regardless of the publication date, were eligible for this review. All types of study designs were eligible with the exception of reviews and meta-analyses. This encompassed experimental or quasi-experimental studies (e.g., randomized controlled trials, non-randomized controlled trials, cluster randomized controlled trials), observational studies (e.g., longitudinal or cohort studies, case-control studies, cross-sectional studies, case reports) and qualitative studies. Only experimental and quasi-experimental studies were considered as providing high-level evidence since they established causal links between finger use and children's arithmetic development. Observational and qualitative studies were considered as providing medium- or low-level evidence (Brighton et al., 2003; Murad et al., 2016).

2.3 Information Sources and Search

An extensive literature search was conducted in January 2021 and updated in November 2021. Two main electronic databases were consulted: Ovid PsycINFO and Ovid ERIC. The search strategies (described in Table S1 in the supplementary material), which combined text words and, when relevant, controlled vocabulary tailored to each database, were performed with the help of a specialist with experience in evidence synthesis (ND). The reference lists of all included documents were searched for any additional papers.

2.4 Selection of the Sources of Evidence

All identified records were uploaded into Covidence software (Covidence Systematic Review Software; Veritas Health Innovation, Melbourne, Australia) and duplicates were removed. Following a pilot test, titles and abstracts were screened by two independent reviewers (MG and MN) according to the eligibility criteria. Then, the full texts of selected studies were assessed by the same two reviewers. At both stages, discrepancies between the two reviewers during selection process were resolved through discussion or by consulting an additional reviewer (LR).

2.5 Data-Charting Process

2.5.1 Data Collection Process

The data were extracted by the two main investigators (MG and MN) using a data-charting form, which was first pretested on a small sample of studies (*n*=4). This form was then adjusted by adding or specifying data to be extracted. Thereafter, data on 20% of the included studies (*n*=14) were extracted blindly and compared to evaluate the inter-rater agreement. Since the agreement was high (i.e., Kappa index = 0.812), half the remaining included studies (40%) were randomly assigned to one of the two investigators, while the other half (40%) was assigned to the other investigator. When uncertainty about some of the extracted data existed, the article was set aside and reconsidered independently by both investigators until agreement was reached (*n*=1).

2.5.2 Data Charting

The data-charting form was built around five main topics: (1) studies' characteristics; (2) participants' characteristics; (3) description of the experimental tasks; (4) main results and, if relevant, the significance and effect size of the statistics used; and (5) the authors' interpretation of the results.

Effect size magnitudes were described using the Cohen's benchmarks (1988). Correlations (*r*) of .10, .30, .50, R-square of .02, .13, .26 and Eta-square of .01, .06, .14 were considered as small, medium and large, respectively. When multiple outcomes of interest were reported, range of effect sizes were then considered.

2.6 Data Items

Because the publication dates of the studies included range between 1938 and 2021, different terms were used to label the participants' cognitive or medical profiles. All of these terms are recorded in Table 1 and grouped under a single dedicated appellation based on the Medical Subject Headings (MeSH) (with the relevant abbreviation) used throughout this scoping review.

Table 1 List of terms identified and their corresponding dedicated appellations and abbreviations.

	Terms used in the included studies	MeSH terms (abbreviations) used in this scoping review
Motor disorders	Developmental coordination disorders	Developmental Coordination Disorders (DCD)
	Cerebral Palsy	Cerebral Palsy (CP)
Learning disorders	Moderate learning difficulties Learning disabilities Learning impairment	Unspecified Learning Disorders (Unspecified LD)
	Reading disabilities Reading difficulties Reading and writing backwardness Specific language impairment	Developmental Language Disorders (DLD)
	Mathematics disabilities Mathematics learning difficulties Mathematical difficulty Mathematics or mathematical learning disabilities Arithmetic disabilities	Mathematical Learning Disabilities (MLD)[a]
	Mentally defective children Moderate intellectual disabilities Mentally retarded children	Intellectual Disabilities (ID)
Other congenital disorders	Spina bifida Spina bifida myelomeningocele	Spina Bifida (SB)
	Extremely low birth weight children Extremely preterm children Preterm children	Preterm Birth Children (PB)
	Congenital heart disease with abnormal neurological development	Congenital Heart Disease (CHD) with abnormal neurological development
	Deafness	Deafness (Df)
	Physical and neurological abnormalities	Physical and Neurological Abnormalities (PNA)[b]

Note. [a] not indexed as MeSH term but the most frequently used term in the literature over the last 20 years; [b] not indexed as MeSH term but the term used by Strauss and Werner (1938).

Among finger sensorimotor skills, the terms *finger schema*, *finger gnosia*, *finger localization* and *finger differentiation* were grouped under the generic term *finger gnosia,* defined as the ability "to differentiate one's fingers when they are out of view" (Malone et al., 2020, p. 1168). The terms *fine motor skills/abilities/coordination*, *finger/manual dexterity*, *eye-hand coordination* and *hand skills*, were grouped under the generic term *fine motor skills,* defined as "small muscle movements requiring close eye-hand coordination" (Luo et al., 2007, p. 596) and distinguished from graphomotor and writing skills (Carlson et al., 2013; Suggate et al., 2018).

2.7 Critical appraisal of individual sources of evidence

Since this scoping review aimed to map all available evidence, no bias risk assessment or quality appraisal of the included studies was conducted. This approach is consistent with the methods manual published by the Joanna Briggs Institute (Aromataris & Munn, 2020).

2.8 Synthesis of Results

The synthesis focused on describing the characteristics and the results of the source of evidence.

3 Results

3.1 Selection of Sources of Evidence

Of the 4,707 studies identified in the two electronic databases, 68 studies met the eligibility criteria and were therefore included. The additional searches in the reference lists of these articles led to the addition of 7 relevant studies. At the end of the selection process, 75 studies were included. The full selection process is documented in the PRISMA flow chart (Figure 1).

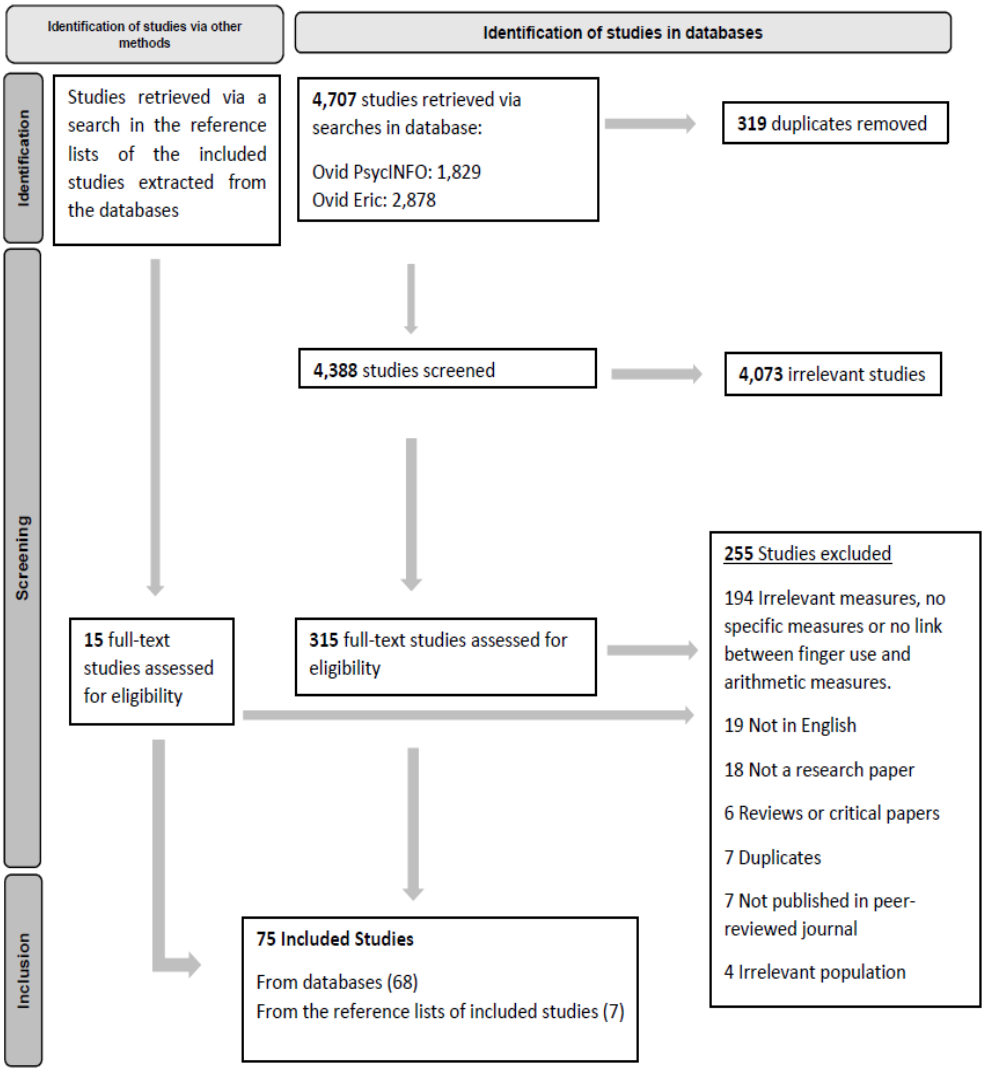

Figure 1. PRISMA flow chart illustrating the selection process.

3.2 Characteristics of Sources of Evidence

3.2.1 Study Designs

Ninety-two percent (*n*=69) of the included studies were conducted with quantitative methods while 8% used qualitative methods (*n*=6). Of the quantitative studies, 52.2% were cross-sectional studies (*n*=36), 21.7% were cluster, randomized, or non-randomized controlled trials (*n*=15), 20.3% were longitudinal or cohort studies (*n*=14), and 2.9% were case-control studies (*n*=2). Two study (2.9%) combined two designs. (See Table S2 in the supplementary material for further characteristics of the included studies.)

3.2.2 Countries of Origin

The studies were conducted in 19 different countries on four continents: the Americas (38%, *n*=29; most represented country: USA, *n*=24), Europe (43%, *n*=33; most represented country: UK, *n*=11), Asia (12%, *n*=9; most represented countries: Japan (*n*=2) and Turkey (*n*=2)) and Oceania (4%, *n*=3, all from Australia). Three percent of the studies (*n*=2) resulted from international collaborations between the USA and China (*n*=1) or India (*n*=1).

3.2.3 Participants

Sixty-two percent (*n*=46) of the included studies were carried out with typically developing children (TD children), 13% (*n*=10) were conducted only with children with atypical development (children with aTD) and 25% (*n*=19) were conducted with both TD children and children with aTD. In the following paragraphs, we summarize participant characteristics: cognitive profiles, grade level or age, and type of education in which they were enrolled. Because most studies did not focus on a single population, many were referenced multiple times.

With regard to studies conducted in TD children (*n*=67), participants were young preschoolers (6%, *n*=4), kindergartners or children in primary school (86.5%, *n*=58) and/or adolescents in secondary school (6%, *n*=4). One study (1.5%) did not report any information about the participants' grade level or age. When the type of education was specified (83.6%, *n*=56), participants were always enrolled in mainstream education.

Studies conducted in participants with aTD (*n*=46) included participants with motor disorders (32.6%, *n*=15), learning disorders (37%, *n*=17), intellectual disabilities (8.7%, *n*=4) or other congenital disorders (21.7%, *n*=10). These participants were preschoolers (2.2%, *n*=1), kindergartners or children in primary school (78.3%, *n*=36) and/or adolescents in secondary school (15.2%, n=7). Two studies (4.3%) provided no information about the participants' grade level or age. Of the studies that mentioned the type of education (65.2%, n=30), a majority of participants with aTD were enrolled in mainstream education (66.7%, n=20). The others were enrolled in special education (33.3%, n=10). See Figure 2 for further details.

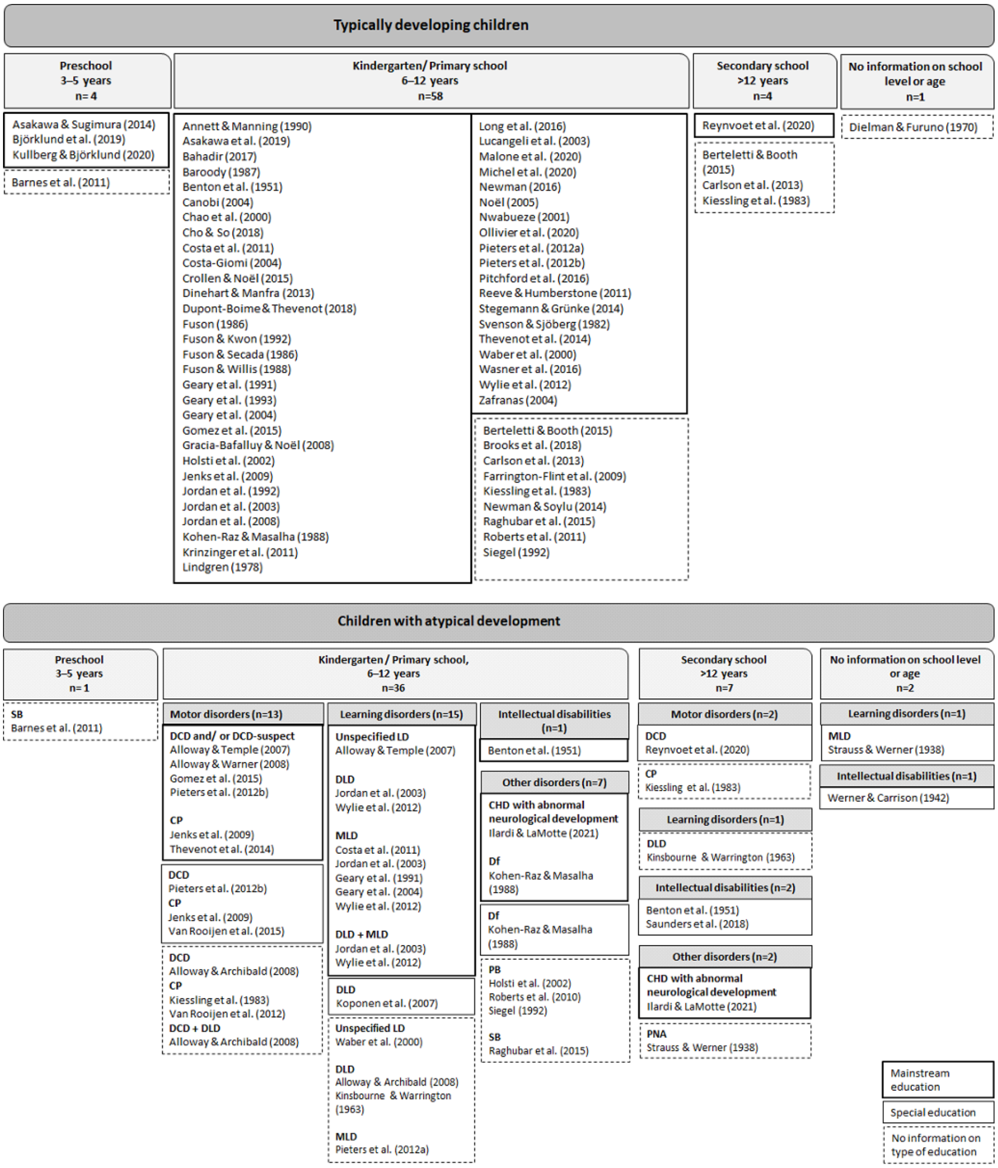

Figure 2. Overview of Studies Involving TD Children and Children with aTD by Grade Level, Age and Type of Education.

Note. SB = Spina Bifida; DCD = Developmental Coordination Disorders; CP = Cerebral Palsy; DLD = Developmental Language Disorders; Unspecified LD = Unspecified Learning Disorders; MLD = Mathematical Learning Disabilities; CHD = Congenital Heart Disease; Df = Deafness; PNA = Physical and Neurological Abnormalities.

3.3 Results of Individual Sources of Evidence

This section summarizes the results of the 75 studies included in this scoping review (see distribution in Figure 3). Firstly, 38.7% percent of them (*n*=29) sought to *determine what finger strategies are used by participants during computation throughout development and how they support arithmetic performance.* We have classified these studies as belonging to the research field of mathematical education. Then, 60% of them (*n*=45) aimed to identify *the cognitive processes and neurobiological mechanisms underlying the relation between fingers and arithmetic* and were classified as belonging to the research area of cognitive psychology and neuroscience. Only one study (1.3%) combined methods from the two research areas, bridging the gap between them. Throughout this section, the results of these three classes of studies are presented with consideration of the type of study design (quantitative studies are presented from high to low level of evidence (Brighton et al., 2003), followed by qualitative studies). The main results are listed in Table S3 in the Supplementary Material and summarized in Figure 4.

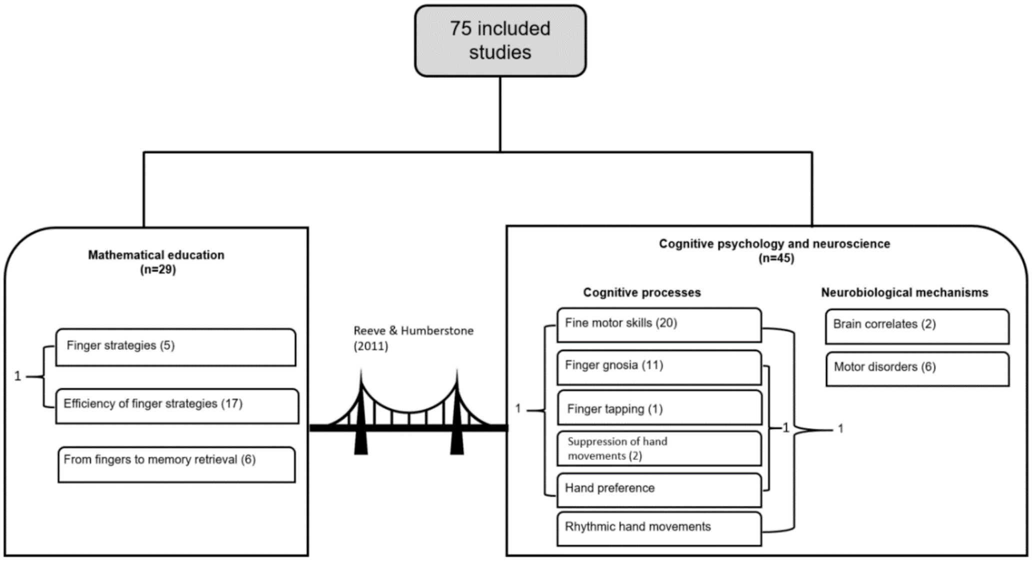

Figure 3. Distribution of included studies

3.3.1 Mathematical Education

For the mathematical education studies (*n*=29), three main research objectives were identified. The first was to describe the finger-based strategies children use during calculation (classified in Figure 3 as "Finger strategies," *n*=5, 17.2%). The second objective was to explore the efficiency of finger-based strategies as a tool to support children's arithmetic performance (classified in Figure 3 as "Efficiency of finger strategies," *n*=17, 58.6%). The last was to investigate how children switched from finger-based to memory-based strategies over time (classified in Figure 3 as "From fingers to memory retrieval," *n*=6, 20.7%). One study (3.5%) that presented two separate experiments was classified in two categories.

Finger-Based Strategies in Calculation. Of the six studies focusing on finger-based strategies, one was a cross-sectional study and five were conducted with qualitative designs.

The cross-sectional study was carried out with TD children who were expert in the use of a mental abacus[2] (Brooks et al., 2018); the number of gestures and gesture sizes produced when calculating one- or two-digit additions were assessed. The results showed that the children gestured more when they solved complex addition problems than for simple addition.

Five qualitative studies were conducted in TD children. The main purpose of these studies was to document how children used their fingers spontaneously when they solved addition (Baroody, 1987; Fuson & Kwon, 1992; Kullberg & Björklund, 2020; Nwabueze, 2001) or subtraction problems (Björklund et al., 2019; Fuson & Kwon, 1992; Kullberg & Björklund, 2020; Nwabueze, 2001). The analyses revealed that participants used a variety of finger-based strategies constituting an embodied representation of ordinal and cardinal information conveyed by numbers including finger-counting strategies in which fingers were folded and unfolded sequentially, cardinal strategies in which fingers were used as cardinal sets, or a combination of both.

Efficiency of Finger-Based Strategies in Calculation. The 18 studies conducted on the efficiency of finger-based strategies as a tool to support children's arithmetic performance comprised one cluster randomized controlled trials, two within-subject randomized controlled trials, five non-randomized controlled trials, one cohort study, one case-control study, seven cross-sectional studies and one qualitative study.

The cluster randomized controlled trial (Chao et al., 2000) was conducted in TD kindergartners and contrasted finger-users and non-finger-users. Arithmetic skills were trained in two programs using either abstract manipulatives (i.e., numbers were represented by sets of abstract objects such as dots) or concrete manipulatives (i.e., number were represented by sets of concrete objects such as cars or apples). The results showed that, among finger-users, training with concrete manipulatives was

[2] Mental computation technique in which children use specific gestures imitating bead manipulation on an abacus.

more effective in increasing their calculation performance than the use of abstract manipulatives.

The two within-subject randomized controlled trials aimed at clarifying which, and to what extent, finger strategies are necessary in performing arithmetic tasks with and without mental abacus in TD children. For mental abacus (Cho & So, 2018), the comparison of three experimental conditions (i.e., physical abacus, hands free during mental abacus use, hands restricted during mental abacus use) in beginning, intermediate and advanced learners showed that gesture was important for beginning and intermediate learners to solve computation but not for advanced leaners. In Brooks et al.'s (2018) study, participants were asked to calculate in four conditions: control condition, without visual feedback, without proprioceptive feedback, or without motor planning. Their results showed that children were less efficient in the fourth condition than the other three, suggesting that, more than gestures, it is motor planning that plays the most important role in advanced learners' computation with a mental abacus.

Five non-randomized controlled trials were conducted in TD primary school children. In four of them, participants were trained to explicitly use finger strategies to solve addition and subtraction problems (Fuson, 1986; Fuson & Secada, 1986; Fuson & Willis, 1988; Ollivier et al., 2020). A significant improvement in calculation performance was consistently observed after training. In the last study, Stegemann and Grünke (2014) trained children using the Chisanbop finger counting method.[3] This training yielded inconclusive results as second-graders did not show a significant improvement in their calculation performance, whereas fifth-graders in the control group improved their performance but not those in the training group.

[3] A Korean finger counting method in which each finger has a number value. The fingers of the right hand count as one except for the thumb, which counts as five, while the fingers of the left hand count as ten.

In the cohort study, Jordan et al. (2008) followed TD kindergartners until the second grade and found small to large correlations between finger use and arithmetic performance, which decreased significantly over time.

In the experimental case-control study, three adolescents with ID were trained with a video intervention to solve addition and subtraction problems using finger strategies. The results showed an enhancement of their calculation performance following the intervention (Saunders et al., 2018).

Seven cross-sectional studies were carried out. Some of them showed how finger-based strategies can influence children's computation performance (*n*=3). Thus, Farrington-Flint et al. (2009) and Lucangeli et al. (2003) examined spontaneous finger-based strategies used to solve computation problems in TD participants enrolled in grades 1 to 5 and showed that the use of finger-based strategies was related to higher-level arithmetic performance. However, cluster analyses carried out in TD children led to distinguishing three groups of finger users in arithmetic tasks: (1) an efficient-count group of children who made efficient use of fingers; (2) an inefficient-count group of children who used their fingers inefficiently; and (3) a flexible group of children with mixed performance (Canobi, 2004).

Other cross-sectional studies contributed to isolating cognitive or demographic factors that could influence the relationship between finger use and computation performance (*n*=4). Regarding demographic factors, Jordan et al. (1992) showed that middle-income TD children used finger-based strategies more often and more efficiently than low-income TD children. Concerning cognitive factors, Newman and Soylu (2014) compared the calculation skills of right-handed TD children who started counting with their right hand with those of children who started with their left hand and showed that right-starters are more efficient at solving single-digit addition problems than left-starters. Comparing kindergartners with a high working memory with children with a low working memory, Dupont-Boime and Thevenot (2018) showed, with strong correlations, that arithmetic performance and finger strategies were closely related and that children with a low working memory use less mature finger strategies than their peers with higher working memory. Comparing the computation skills of first-, third- and fifth-graders with MLD and working memory deficits to those of TD children, Geary et al. (2004) showed that children with MLD used finger counting more often but were less accurate than TD children.

Finally, one action research qualitative study conducted with TD children showed the effectiveness of a training program in which children learned to solve multiplication problems with finger strategies (Bahadir, 2017).

From Finger-Based to Memory-Based Strategies. Of the six studies conducted to describe how finger-based strategies evolve over time, four were longitudinal or cohort studies, one was a case-control study and one used a cross-sectional design.

The four longitudinal or cohort studies were conducted in children with TD or aTD. First, Svenson and Sjöberg (1982) followed TD children from the first to the third grade and showed that children switched from finger-based to memory-based strategies during this period. Geary et al. (1991) followed children with TD or MLD from the first to the second grade and showed that children with MLD used finger counting more often and made more counting errors than TD children. In the Wylie et al. (2012) and Jordan et al. (2003) studies, children with TD, DLD, MLD and DLD+LMD were followed from the second to the third grade (i.e., between 5 and 7 years of age). Wylie et al. (2012) showed that children with MLD and DLD+LMD made more frequent use of finger counting and switched to memory-based strategies later than children with TD and DLD. The difference between these groups was of medium effect size. Similarly, Jordan et al. (2003) showed that participants with MLD used finger counting more frequently and were more accurate than children with DLD+MLD. Moreover, children with MLD had more difficulty switching from finger-based to memory-based strategies than the other groups.

Koponen et al. (2007) conducted one experimental case-control study in which two children with DLD were trained to switch from finger-based strategies to memory-based strategies in solving single-digit addition problems. One of the two children improved his performance by substituting fact retrieval for finger counting.

Finally, one study used a cross-sectional design to compare calculation strategies used by Chinese and American TD kindergartners (Geary et al., 1993). Interestingly, this switch from finger-based to memory-based strategies occurred earlier in Chinese children than in their American peers. These group differences had medium to large effect sizes.

3.3.2 Cognitive Psychology and Neuroscience

Forty-five studies from the cognitive psychology and neuroscience field investigated the cognitive processes and neurobiological mechanisms underlying the relationship between finger abilities and arithmetic skills. Studies exploring cognitive processes (*n*=37, 82.2%) focused either on one finger sensorimotor skill (i.e., fine motor skills: *n*=20, finger gnosia: *n*=11, finger tapping: *n*=1; suppression of hand movements: *n*=2) or on a combination (i.e., fine motor skills + rhythmic movements: *n*=1, fine motor skills + hand preference: *n*=1; finger gnosia + hand preference: *n*=1). Eight studies (17.8%) explored the neurobiological mechanisms either by investigating the computation skills of children with fine motor disorders (*n*=6; children with DCD or CP) or by documenting the cerebral correlates underlying finger use and arithmetic abilities (*n*=2).

Cognitive Processes.

Fine Motor Skills and Arithmetic. The 22 studies focusing on fine motor skills (FMS) comprised one randomized controlled trial, three non-randomized controlled trials, seven cohort or longitudinal studies, and 11 cross-sectional studies.

In the randomized controlled trial (Asakawa et al., 2019), school-aged TD participants were trained in FMS. The results showed that children in the training group improved not only their FMS but also their arithmetic skills, unlike those in the control group. The improvements had medium to large effect sizes.

Three studies were non-randomized trials in which children with TD or aTD were trained in FMS. Zafranas (2004) gave TD children a piano training program and showed a joint improvement in FMS and arithmetic skills in the training group, but not in the control group. Conversely, two other studies reported no improvement in arithmetic skills following FMS training in children with TD (Costa-Giomi, 2004; piano lessons) or DCD (Alloway & Warner, 2008), but there was an enhancement in FMS, self-esteem or visuospatial working memory.

The seven cohort or longitudinal studies investigated whether early FMS predict the development of children's arithmetic skills several years later. Six of them showed that FMS were a significant predictor of arithmetic skills, with effect sizes ranging from very small to large (Asakawa & Sugimura, 2014; Barnes et al., 2011; Dinehart & Manfra, 2013; Jenks et al., 2009; Siegel, 1992; VanRooijen et al., 2015). However, one study showed that the predictive value of FMS failed to reach significance when executive functions were added to the statistical model (Michel et al., 2020).

Finally, 11 cross-sectional studies were conducted with children with TD and aTD. Comparative or correlational models showed a significant association between FMS and arithmetic skills in seven studies, with effect sizes ranging from small to large (Annett & Manning, 1990; Dielman & Furuno, 1970; Holsti et al., 2002; Pieters, Desoete, Roeyers, et al., 2012; Pieters, Desoete, Van Waelvelde et al., 2012;Raghubar et al., 2015;VanRooijen et al., 2012). Less conclusive results were found in two other studies, which reported a significant association between arithmetic and FMS of the right hand but not the left hand (Kiessling et al., 1983), or in first-graders but not in kindergartners (Pitchford et al., 2016). Only fine motor integration (i.e., "manual ability which requires synchronized hand-eye movements and the processing of visual stimulus in order to produce adequate motor output," assessed by drawing geometric shapes; Pitchford et al., 2016, p. 2) was correlated with calculation skills. Finally, two studies found no significant relationship between FMS and arithmetic skills (Carlson et al., 2013; Ilardi & Lamotte, 2021). In these studies, calculation skills were respectively related to fine motor integration (after controlling for gender, age and IQ) and perceptual reasoning, processing speed and working memory, but not to FMS.

Finger Gnosia Abilities and Arithmetic. Among the 12 studies examining the relation between finger gnosia and arithmetic skills, there were one non-randomized trial, two longitudinal studies, eight cross-sectional studies and one combining cross-sectional and case report designs.

In the non-randomized controlled trial, TD participants followed finger gnosia training based on fine motor activities. In their results, Gracia-Bafalluy and Noël (2008) showed a concurrent improvement in both finger gnosia and arithmetic skills specific to the training group.

The two longitudinal studies yielded contrasting results about the predictive value of TD first-graders' finger gnosia on their arithmetic skills assessed one year later. The first showed that finger gnosia were a significant predictor of computation skills, with a medium effect size (Noël, 2005), while the second concluded that only number knowledge and numerosity discrimination were significant predictors of arithmetic development, but finger gnosia was not (Malone et al., 2020).

Nine studies were cross-sectional**,** comparing two groups of children with different cognitive profiles (i.e., TD vs. MLD and TD vs. ID) or focusing on the relationship between finger gnosia and arithmetic skills in a specific population (i.e., TD, MLD or ID children). The results of three studies showed a significant association between finger gnosia and arithmetic skills, with effect sizes ranging from small to medium (Costa et al., 2011; Lindgren, 1978; Wasner et al., 2016). Conversely, Long et al. (2016) concluded that there was no evidence concerning the relation between finger gnosia and arithmetic skills after the effect of age was controlled. Furthermore, in Newman's (2016) study, the results were mixed. The author concluded that a significant association existed between finger gnosia and computation skills in older children but not in younger ones. The results of the last four studies were contrasting. Two of them supported the finger gnosia/arithmetic relation (Kinsbourne & Warrington, 1963; Werner & Carrison, 1942), while the other two concluded that there was no relation (Benton et al., 1951; Strauss & Werner, 1938).

Finally, Strauss and Werner (1938) also provided a case report describing the cognitive profile of an adolescent who had both finger recognition and arithmetic impairments. The results were in line with the existence of a relation between the two deficits.

Other Finger Abilities and Arithmetic. Finally, of the seven last studies, one was a cross-sectional study focusing on finger tapping in which arithmetic skills and finger tapping in children with unspecified LD and their TD peers were assessed. Using a correlation model, Waber et al. (2000) showed that finger tapping was a predictor of the numerical skills in both populations.

Two studies aimed at examining the influence of finger movement suppression on arithmetic performance in deaf and TD children. Using a within-subject randomized controlled trial, Crollen and Noël (2015) asked to their participants to solve problems in three different interference conditions (i.e., squeezing a ball with a hand, squeezing a ball with a foot and a control condition) and showed that children were less efficient in the hand interference condition than in the other two conditions, suggesting that gestures play a functional role in calculation skills. The difference was of medium to large effect size. The second study showed, with a correlational models, that ability to suppress finger synkinetic movements during arithmetic task is positively associated with arithmetic performance both in deaf and typically developing children, with effect sizes ranging from small to large (Kohen-Raz & Masalha, 1988).

Two studies yielded contradictory evidence about the influence of hand preference in TD children through a cross-sectional design comparing right or left hand use and arithmetic skills. Annett and Manning's (1990) results showed that right-handers were more efficient than left-handers at calculation tasks, while Newman (2016) did not find a significant association between hand preference and arithmetic skills in participants.

Finally, one study with a longitudinal design explored the relation between rhythmic hand movements and arithmetic skills in TD children followed from 4 to 6 years old (Asakawa & Sugimura, 2014). Rhythmic hand movements were not found to have a predictive value regarding arithmetic skills.

Neurobiological Mechanisms

Cerebral Correlates. Two of the included cross-sectional studies explored the cerebral correlates underlying finger use and arithmetic skills in TD children (Berteletti & Booth, 2015; Krinzinger et al., 2011). They examined brain activations in the motor cortex (i.e., intraparietal sulcus) involved in finger movements while children were solving arithmetic problems. Krinzinger et al. (2001) showed that finger-related brain areas were more activated during calculation than during a magnitude comparison task. Berteletti and Booth (2015) found that, in children between 8 and 13 years old, the "finger motor cortex" (i.e., brain areas related to FMS) was more activated during subtraction than the "finger somatosensory area" (i.e., brain areas related to finger gnosia). These results support the existence of a relation between finger movements and arithmetic skills.

Congenital and Neurodevelopmental Motor Disorders. Six studies were conducted with children with non-progressive congenital motor pathologies detected at birth (e.g., cerebral palsy, CP) or neurodevelopmental motor disorders (e.g., developmental coordination disorders, DCD) aged from 8 to 12. These cross-sectional studies compared the arithmetic skills of motor-disabled participants with those of TD children or children with other developmental pathologies. Roberts et al.'s (2011) results showed that preterm children with DCD had more arithmetic difficulties than those without DCD. Gomez et al.'s (2015) study produced contrasting results: children with DCD were significantly slower at solving calculation problems than TD children but no less accurate. Of the last four studies, two showed that children with DCD performed similarly to their peers with DLD and unspecified LD at solving calculation problems (Alloway & Archibald, 2008; Alloway & Temple, 2007). The two remaining studies came to the same conclusion comparing children with CP and DCD with their TD peers (Reynvoet et al., 2020; Thevenot et al., 2014).

3.3.3 Study Combining Mathematical Education and Cognitive Psychology and Neuroscience Methods

Ultimately, only one cross-sectional study (Reeve & Humberstone, 2011) of the 75 studies included here combined research methods applied in mathematical education and in cognitive psychology and neuroscience, building a bridge between these two research fields. This study was carried out with TD children aged from 5 to 7 years old in order to determine whether finger gnosia was associated with calculation efficiency and finger counting. First, using latent class analyses, the participants were split into four different subgroups based on both their accuracy in arithmetic and the finger strategy they used during calculation: (1) low finger use and low accuracy, (2) low finger use and successful performance, (3) high finger use and moderate accuracy, and (4) moderate finger use and moderate accuracy. The same kinds of analyses were done to develop four finger gnosia profiles: (1) finger/hand confusion, (2) finger confusion, (3) good finger gnosia, and (4) high finger gnosia. Multimodal logistic regression analyses were conducted and showed a significant relationship between finger gnosia, arithmetic performance and finger strategies beyond the contribution of visuospatial working memory, suggesting that a relation exists between finger gnosia and finger counting. The effect size for this association was large.

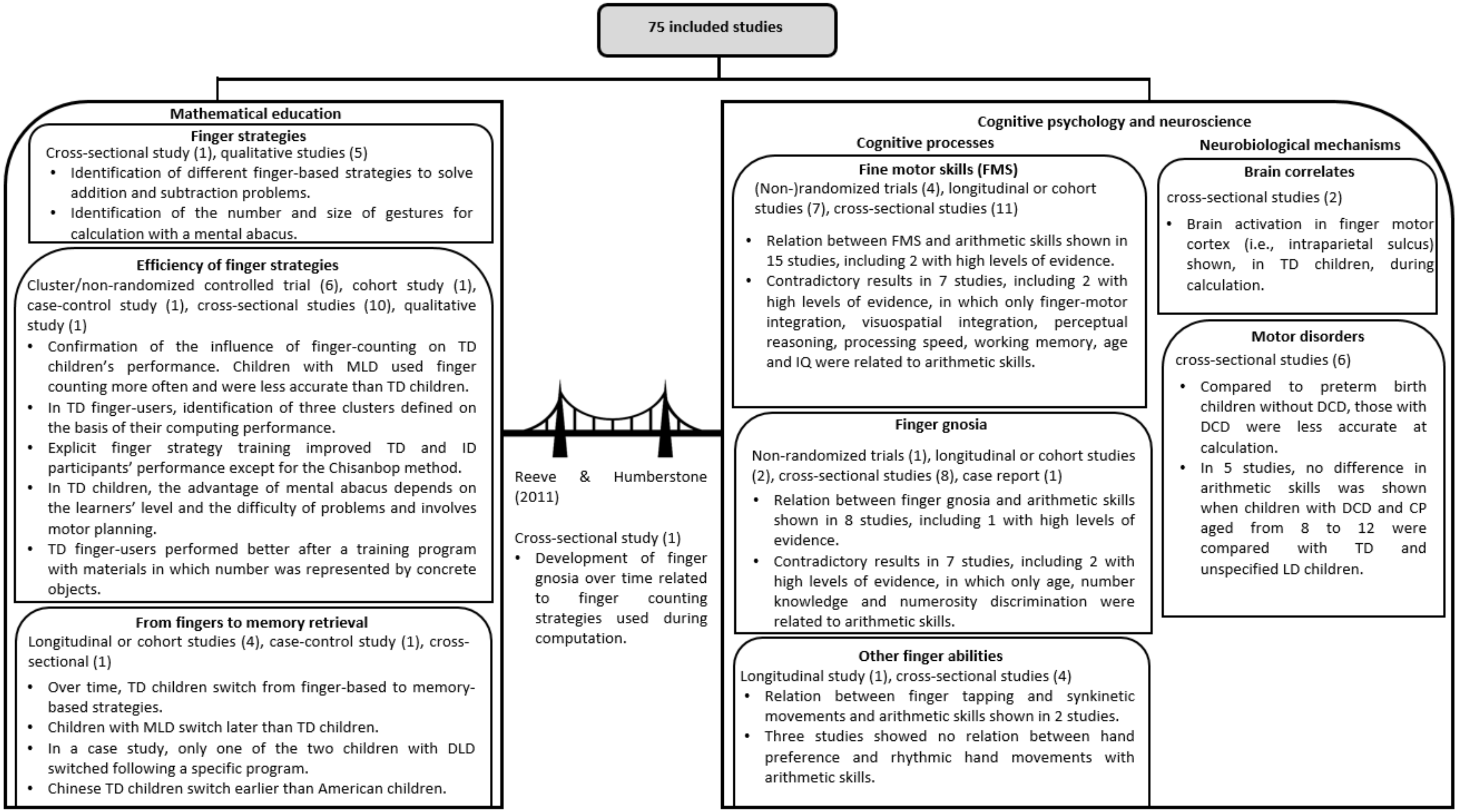

Figure 4. Summary of findings from different sources of evidence

4 Discussion

The main objective of this scoping review was to identify all the qualitative and quantitative studies that have explored the relationship between finger use and arithmetic skills in school-aged children and adolescents. At the end of the selection process, 75 studies were included. Their results were discussed in two main sections, starting with the characteristics of the studies' samples and then conducting an analysis.

4.1 Analyses of Characteristics of Study Samples

Descriptive analysis of the study samples showed that there was no major imbalance in the proportion of studies conducted in TD children (59%) and in children with aTD (41%). In contrast, we found a large disparity in the age of participants: only a minority of studies were conducted in preschoolers (6%) or in adolescents enrolled in secondary school (6%). Regarding studies conducted in children with aTD, our results showed that participants with intellectual disabilities were under-represented (8.7%) compared with other children (i.e., motor disorders: 32.6%, learning disorders: 37% and other congenital disorders: 21.7%). A minority of these studies were conducted with children enrolled in special education (33.3%). Not surprisingly, since arithmetic skills are primarily taught in elementary school, the majority of studies published to date were conducted with children at this grade level. Given the predictive value of the pre-arithmetic skills for future computational abilities (Watts et al., 2014), longitudinal studies conducted from preschool through primary school grades would provide insight into whether the use of fingers should be promoted as a tool to prevent mathematics difficulties in younger children. Furthermore, a closer look at the influence of finger counting in children with aTD, especially when enrolled in special education, would inform us about whether finger counting can be used with this population as an appropriate accommodation during mathematics lessons. Such studies should be conducted more specifically with participants with intellectual disabilities who are under-represented compared to other participants with aTD.

4.2 Analyses of Individual Sources of Evidence

An initial analysis of individual sources of evidence from the 75 included studies showed that two main research topics were addressed in these studies: (1) What kinds of finger-based strategies do participants use during computation over the course of development, and how do they support arithmetic performance? (2) What cognitive processes and neurobiological mechanisms underlie the relationship between fingers and arithmetic?

4.2.1 What Kind of Finger Strategies Do Participants Use during Computation over the Course of Development and How Do They Support Arithmetic Performance?

The studies conducted in the mathematical education field had three main objectives: (1) describing the finger-based strategies children use when calculating (20%); (2) exploring how finger-based strategies support children's arithmetic performance (60%); and (3) investigating how these finger-based strategies change during the child's development (20%).

In studies describing strategies used to solve arithmetic problems, finger strategies were found to be used in various ways either to count (e.g., folding and unfolding fingers sequentially) or as cardinal sets (e.g., thumb, index and middle finger raised to indicate 3) (Baroody, 1987; Björklund et al., 2019; Fuson & Kwon, 1992; Kullberg & Björklund, 2020; Nwabueze, 2001). When children solved complex addition problems with a mental abacus, they made many gestures imitating the manipulation of beads on an abacus (Brooks et al., 2018). There was a strong imbalance in the proportion of studies conducted with qualitative designs (75%) versus quantitative designs (25%). Additional quantitative evidence is needed to confirm the observations made in the qualitative studies. With new evidence of that kind, it would be possible to clarify the most useful finger strategies in arithmetical contexts to inform teachers of best practices to be promoted in class.

In the studies conducted to explore how finger-based strategies might support children's computational skills, the results indicated that finger-based strategies

(Canobi, 2004; Dupont-Boime & Thevenot, 2018; Farrington-Flint et al., 2009; Jordan et al., 1992; Lucangeli et al., 2003; Newman & Soylu, 2014) or a mental abacus (Brooks et al., 2018; Cho & So, 2018) could promote TD participants' computational performance. Moreover, computation skills were found to be improved by different kinds of explicit training of finger-based strategies (Fuson, 1986; Fuson & Secada, 1986; Fuson & Willis, 1988; Ollivier et al., 2020; but see Stegemann & Grünke, 2014, for inconclusive results of training with the Chisanbop method). The studies also showed that children with MLD use more finger-based strategies and make more calculation errors than their TD peers when solving addition problems (Geary et al., 2004). A minority of these studies were conducted using a high level of evidence design (i.e., cluster, non-randomized or randomized controlled trial) (44.4%) compared with research carried out with medium and low level of evidence designs (i.e., cohort study, case-control study, cross-sectional study or qualitative study) (55.6%). Only 33% of them showed, through a randomized controlled trial, an improvement of arithmetic skills following a finger-based strategies training. More randomized controlled trial would be necessary to confirm the results reported in case-control or cross-sectional studies and would provide stronger evidence of the functional links between finger-based strategies and arithmetic performance in TD children. Moreover, additional studies should be conducted with participants with MLD, who are still under-examined, to confirm the initial evidence. Finally, further training studies with TD children and participants with aTD could help identify the most effective finger-based strategies to be targeted as a function of cognitive profile. This evidence could also inform the most effective educational approaches to be used when teaching finger-based strategies in children with TD and aTD.

Finally, six studies were conducted to investigate how finger-based strategies change throughout childhood. These studies showed that, over time, TD children naturally switch from finger-based to memory-based strategies (Svenson & Sjöberg, 1982), but that children with MLD switch later in their development than their TD peers (Geary et al., 1991; Jordan et al., 2003; Wylie et al., 2012). However, no switching was found in children with DLD and mathematical difficulties, even after an explicit training program (Koponen et al., 2007). A separate body of literature showed that working memory is important for children's arithmetic development, since good working memory is a prerequisite for detaching from external support (e.g., fingers or concrete manipulatives) in favor of mental strategies for solving computations. A working memory deficit in children with LMD could explain why they find it difficult to switch to abstract computation strategies such as memory retrieval (see David, 2012; Friso-Van Den Bos et al., 2013; Peng et al., 2016, for meta-analyses). Returning to the results of this scoping review, only one study was conducted with children with DLD to train them to switch from finger-based strategies to memory retrieval. Additional training studies involving children with MLD are needed to target interventions and therapeutic tools to be promoted to help them switch to memory-based strategies so that they can become more efficient at calculating and solve more complex problems. Finally, studies should be conducted to determine whether switching from fingers to memory strategies is mediated by finger sensorimotor skills such as fine motor skills or finger gnosia.

4.2.2 *What Cognitive Processes and Neurobiological Mechanisms Underlie the Relation between Fingers and Arithmetic?*

The studies conducted in the cognitive psychology and neuroscience research areas had one of two objectives: investigating the cognitive process (81.8%) or examining the neurobiological mechanisms (18.2%) that underlie the relation between finger movements and arithmetic skills.

With regard to *the cognitive process*, the impact of six finger abilities on arithmetic skills has been investigated. Fine motor skills (FMS) (55%) and finger gnosia (30%) were explored more often than finger tapping (2.5%), suppression of hand movements (5%), hand preference (5%) and rhythmic hand movements (2.5%).

The majority of studies of the relation between FMS and computation supported the existence of such a relation (68.2% favorable vs. 31.8% unfavorable). One randomized controlled trial (Asakawa et al., 2019) and one non-randomized controlled trial (Zafranas, 2004) were in line with this conclusion while two non-randomized controlled trials were not (Alloway & Warner, 2008; Costa-Giomi, 2004). Similarly, the majority of studies focusing on finger gnosia supported the idea that it promotes children's arithmetic skills (66.7% favorable vs. 33.3% unfavorable). The study providing the highest level of favorable evidence was a non-randomized controlled trial (Gracia-Bafalluy & Noël, 2008). More randomized controlled trials should be conducted to examine the causal links between FMS or finger gnosia and computation skills. Indeed, although the vast majority of studies concluded that these two abilities support children's arithmetic development, only 60% of randomized and non-randomized controlled trials agreed with this conclusion. Moreover, further randomized controlled trials are needed to determine whether training of these two finger-based abilities should be integrated, in addition to finger counting training, into educational practices and tools. If so, more studies should be conducted to determine how and when such training should be implemented in the classroom.

Regarding the other finger skills, the results showed that finger tapping (Waber et al., 2000) and suppression of hand movements (Crollen & Noël, 2015; Kohen-Raz & Masalha, 1988) were correlated with children's computation skills. However, rhythmic hand movements (Asakawa & Sugimura, 2014) did not appear to predict the development of arithmetic skills. The role of hand preference (Annett & Manning, 1990; Newman, 2016) was unclear since only one study (out of two) suggested that it affected children's arithmetic skills. More generally, given that only six articles have investigated the influence of these finger abilities on children's arithmetic skills, more evidence is needed to gain a clearer picture of this relation.

Finally, in 19.4% of studies, other cognitive (executive functions, perceptual reasoning, processing speed, working memory, fine motor integration, or IQ), demographic (age, socioeconomic status (SES) and gender), or academic (early numerical skills: number knowledge and numerosity discrimination) factors were found to have a large effect on arithmetic development – more than the influence of finger abilities (Carlson et al., 2013; Ilardi & Lamotte, 2021; Long et al., 2016; Malone et al., 2020; Michel et al., 2020; Pitchford et al., 2016). It therefore seems critical to integrate these types of variables more systematically into statistical models to clarify their importance in children's arithmetic development, in comparison to finger abilities.

To investigate the *neurobiological mechanisms* that underlie the relation between finger movements and arithmetic skills, two different methods were used: (1) comparing the arithmetic performance of children with fine motor disorders (DCD and CP), either neurodevelopmental or acquired at birth, with that of children without motor deficits (75%); or (2) investigating the cerebral correlates supporting finger use and arithmetic skills (25%).

Using a behavioral approach, 83.3% of studies carried out in children with DCD or CP aged from 8 to 12 years showed that, despite their motor deficits, these children were able to develop similar calculation performance to their TD peers (Alloway & Archibald, 2008; Alloway & Temple, 2007; Gomez et al., 2015; Reynvoet et al., 2020; Thevenot et al., 2014). Thevenot et al. (2014) hypothesized that children with CP probably compensate for their fine motor disorders with other adaptive skills such as memory-based strategies. Additional studies should be conducted with children with DCD or CP to confirm these first indications and determine which cognitive processes (if any) they use to compensate for their disabilities.

Finally, using fMRI, two studies conducted in TD children supported the existence of a relation between finger use and arithmetic skills, showing brain activation in finger motor areas (within the intraparietal sulcus) during computation (Berteletti & Booth, 2015; Krinzinger et al., 2011). Currently, only these two studies have used fMRI to investigate the relation between finger use and arithmetic. More evidence is therefore necessary for a better understanding of the role of the fingers in arithmetic development.

4.3 Conclusions

In this scoping review, the relation between finger use and arithmetic skills was investigated in 75 studies.

Regarding the studies conducted in *mathematical education*, the results showed that children used a variety of finger-based strategies to support their computational performance and that these strategies tended to disappear during development in favor of memory-based strategies. More studies should be conducted to determine which finger-based strategies are the most effective, taking children's cognitive profile into account, and whether the transition from finger-based to memory-based strategies is mediated by finger sensorimotor skills.

The studies conducted in *cognitive psychology and neuroscience* showed that FMS, finger gnosia, finger tapping and hand movements might promote the development of children's arithmetic skills. Among children with aTD, studies showed that children with DCD and CP aged from 8 to 12 years produced similar computational performance to TD children, suggesting that, early in the child's arithmetic development, other cognitive factors supplant finger skills. Finally, functional neuroimaging data showed that finger-use and arithmetic skills share common, or at least very close, cerebral substrates, providing evidence of a link between these two abilities at the neuroanatomical level. More studies are needed to confirm this evidence and to determine if, when and how finger sensorimotor skill training should be integrated, in addition to finger-based strategy training, into educational practices and tools.

While 49% of the studies conducted in cognitive psychology and neurosciences reported effect sizes, only 21% of those conducted in the field of mathematical education did so. It is important to be able to generalize practices assessing effect sizes to estimate how closely finger counting and finger sensorimotor skills are linked to children's arithmetic performance.

Although these studies have investigated the direct influence of finger-based strategies or finger sensorimotor skills on arithmetic skills, they have not addressed how finger-based strategies are related to finger sensorimotor skills or how this relation influences children's arithmetic skills. Only one study has investigated the relation between finger gnosia and finger-based strategies during computation, bridging the gap between mathematical education research and studies in cognitive psychology and neuroscience. In that study, Reeve and Humberstone (2011) demonstrated the existence of a functional link between these three variables. Additional studies combining educational and cognitive approaches are necessary to confirm these isolated results.

4.4 Prospects for Future Research

This scoping review provides the first methodical summary published to identify all studies that have investigated the relation between finger use and arithmetic skills in children and adolescents. This scoping review lays the groundwork for a systematic review to answer more specific questions and provide teachers, therapists and researchers with clear guidelines for clinical and pedagogical practices. A critical appraisal of the studies included could also be conducted in future to explore the methodological quality of each study and complement the evidence examined here.

Conclusion de la Partie 1

Très tôt dans le développement, les enfants utilisent leurs doigts pour exécuter des *gestes de comptage* qui accompagne la récitation de la chaine numérique verbale ou des *gestes numériques* par lesquels le cardinal associé à un mot-nombre peut être représenté. Certains auteurs suggèrent que ces gestes soutiennent l'élaboration de la chaine numérique verbale ou encore l'apprentissage de certains principes de dénombrement ou de la valeur cardinale des mots-nombres sans, toutefois, que ces propositions ne fassent l'unanimité dans la communauté scientifique. En revanche, la majorité des auteurs semblent s'accorder à dire que ces gestes sont de bons supports au développement des compétences arithmétiques puisque les enfants les utilisent pour représenter les termes des opérations, améliorant ainsi leurs performances en calcul.

A l'heure actuelle, de plus en plus de recherches sont conduites pour mieux comprendre comment ses gestes contribuent au développement numérique et arithmétique des enfants. Peu d'entre elles ciblent spécifiquement les habiletés sensorimotrices (gnosies digitales et les habiletés motrices fines) nécessaires à la fonctionnalité des gestes de comptage et des gestes numériques. A l'heure actuelle, les résultats des études menées sont trop souvent contradictoires pour définir précisément la nature des habiletés sensorimotrices impliquée dans les traitements numériques et les mécanismes qui sous-tendent ces relations. Les quatre études expérimentales conduites dans les deux prochaines parties de cette thèse visent à enrichir la littérature existante sur cette question.

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Partie 2 – Phase expérimentale conduite auprès d'enfants au développement typique

Chapter 4 - Do fine motor skills and finger gnosia predict the development of arithmetic through finger-use? A longitudinal study to investigate the functionalist hypothesis.

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Abstract:

Fine motor skills (FMS) and finger gnosia have been shown to be a key component of arithmetic development, but the processes underlying this relationship are still poorly understood. The aim of this study was to test *the functionalist hypothesis* which assumes that FMS and finger gnosia would support arithmetic development through the use of finger-based calculation strategies. The predictive value of FMS and finger gnosia on arithmetic development was explored, as well as the possible mediating role of finger-use on these relationships. Seventy-four 6-year-old children were assessed on four occasions, between the beginning of grade 1 and the end of grade 2. At each measurement time, they were asked to complete tasks assessing arithmetic skills, finger gnosia and FMS. By conducting latent growth models, the initial value of FMS and its rate of change were not found to be significant predictors of the development of arithmetic skills. Conversely, the initial value and rate of change of finger gnosia were shown to be a key predictor of arithmetic development. Taken together, they explained 43% of arithmetic development between the beginning of grade 1 and the end of grade 2. Latent growth models failed to show that finger gnosia predicted the development of arithmetic skills through finger-use, suggesting that at this stage of development, the origin of the finger gnosia/arithmetic relationship is unlikely to be functional.

Keywords: Fine motor skills, finger gnosia, finger-use, arithmetic, longitudinal study, functionalist hypothesis.

1 Introduction

In the field of the numerical cognition, theories of embodied cognition has attracting increasing attention. These theories postulate that the development of the numerical concepts is deeply rooted in the child's sensorimotor experiences. In the context of mathematical development, the theories assume that symbols and numerical concepts make sense when embedded in bodily experiences (Barsalou, 2008; Moeller et al., 2012; for a review see Andres & Pessenti, 2015). As such, fingers would therefore have a privileged status in the development of numerical and arithmetic skills. Always available and easy to manipulate, fingers provide an embodied representation of various numerical concepts (i.e., cardinality, ordinality, one-to-one correspondence; Bender & Beller, 2011; Crollen et al., 2011; Wasner et al., 2015). Fingers support the internalization of these concepts through the multimodal association (i.e., motor and visual) with numbers (Butterworth, 1999; Fuson et al., 1982; Lakoff & Nunez, 2000).

To achieve functional finger use, children rely on the sensorimotor finger skills required to control and coordinate fingers. A growing body of research has been conducted to determine which sensorimotor finger skills are involved in the development of arithmetic processing. Two categories of sensorimotor skills have been particularly examined. Some research focused on finger gnosia which refer to the representation of finger position on one's own hand (Noël, 2005; Strauss & Werner, 1938). Usually assessed through tactile stimulation, finger gnosia were found to be related to arithmetic skills in children aged six to ten (Fayol et al., 1998; Newman, 2016; Penner-Wilger et al., 2007; Zhang et al., 2020). Taking a developmental approach, Noël (2005) provide evidence that finger gnosia, assessed at the beginning of the first grade (Mean age = 6.8 years), were a specific predictor of children's arithmetic development 15 months later. Recently, the significance of this relationship has been shaded, as finger gnosia were shown to predict a unique but small part of the variance (around 1-2%) in six-year-olds' arithmetic skills, once general cognitive skills (e.g., working memory) and the mastery of numerical precursors (e.g., symbolic comparison) taken into account (Wasner et al., 2016).

Afterwards, motor components, captured usually in object manipulation tasks assessing fine motor skills (FMS) (i.e., ability to move fingers in differentiated ways) have attracted attention. Only a handful of researches conducted on school-age children have specifically targeted arithmetic skills. As such, FMS were found to explained a unique part of the variance in arithmetic skills of five-year-olds who were asked to solve an object-based arithmetic task in which they had to add and subtract non-symbolic quantities (Barnes et al., 2011). FMS assessed at age four have shown to specifically predict children's arithmetic development two years later (Asakawa & Sugimura, 2014). A positive influence of FMS training on arithmetic skills has also been demonstrated in six-year-old children (Asakawa et al., 2019; Gracia-Bafalluy & Noël, 2008; buy see Schild et al., 2020 for opposing results) illustrating the causal mechanisms underpinning this relationship. Recently, Michel et al. (2020) challenged this association in their longitudinal investigation by showing that FMS assessed at age six lost its predictive power on arithmetic skills evaluated two years later, once the influence of executive functions was controlled for.

Taken together, this initial evidence suggests that both finger gnosia and FMS are of particular importance for the development of arithmetic skills. Investigating these sensorimotor finger skills jointly, Asakawa & Sugimura (2022) recently provided evidence that the association of these two components explains a significant proportion of the variance in arithmetic performance of five-year-olds, without specifically determining the part explained by each of these two skills. Precisely estimating the contribution of each variable could nevertheless be decisive in determining whether the acquisition and development of arithmetic skills are more closely linked to finger gnosia or to FMS involved in solving calculations. A closer examination of the processes involved in in these relationships could, moreover, contribute to a better understanding of their nature, which is currently still unclear.

One of the explanatory hypotheses for the origin of the association between sensorimotor finger skills and arithmetic is that they would be linked by a functional relationship (Butterworth, 1999). This hypothesis (known as the *functionalist hypothesis*) assumes that sensorimotor finger skills support the use of finger-based strategies, which, in turn, promote the development of arithmetic processing. Used in the early years of schooling (Geary & Brown, 1991; Jordan et al., 2008) fingers provide young children with an external support for visualizing and combining the quantities involved in a calculation (Baroody, 1987; Björklund et al., 2019; Kullberg & Björklund, 2020; Roesch & Moeller, 2015). When solving complex problems involving several stages of resolution, they also are used to keep track of the results of intermediate calculations (LeFevre et al., 2005).

To our knowledge, only Reeve and Humberstone (2011) have investigated the triadic relationship between finger gnosia, finger-use and arithmetic skills in kindergartners and in first graders (Age range = 5-7 years) in a study that aimed to determine (1) whether finger gnosia were comparable in children from both groups and (2) whether these sensorimotor finger skills predicted finger-use and performance in an additive problem-solving task. After completing a non-motor finger gnosia task and a single-digit addition task, participants were split into four subgroups based on performance in the finger gnosia task and error patterns (i.e., finger-hand confusion, finger confusion, good finger gnosia, high finger gnosia) and into four subgroups formed based on performance in the calculation task and frequency of finger-use (i.e., low finger-use/ low accuracy, low finger-use/ high accuracy, high finger-use/moderate accuracy, moderate finger-use/ moderate accuracy). Results of logistic regression analyses shed light on a significant association between finger gnosia, finger-use and calculation performance. Children with poor finger gnosia were largely assigned to the group of children with low finger-use and poor arithmetic skills, while children with good finger gnosia were assigned to the group of children with good arithmetic skills. This relationship would also be age-related since finger gnosia were more developed in older children, who might in turn rely on these sensorimotor ablities to use their fingers in arithmetic problem solving.

Although pioneering, this work does not provide sufficient evidence to test the *functionalist hypothesis*. Indeed, by focusing on finger gnosia, only the finger representation components were investigated in this work, without taking into account motor habilities. Yet, the FMS seem to play a decisive role in the acquisition of finger-based strategies, which could, in turn, contribute to the development of children's arithmetic skills. To test the *functionalist hypothesis*, FMS could therefore be examined, in association with finger gnosia, to provide a better understanding of the mechanisms underlying the triadic relationship between sensorimotor finger skills/finger-use and arithmetic abilities. At the same time, this approach would make it possible to determine whether finger-use directly supports the development of young children's arithmetic performance, an issue that was not examined in Reeve and Humberstone's (2011) research since these two variables were treated jointly to define the subgroups formed on the basis of performance on the calculation task.

The aim of the present study was to test the *functionalist hypothesis* in the context of arithmetic development. As the triadic association between sensorimotor finger skills, finger-use and arithmetic performance appears to be age-related (Reeve & Humberstone, 2011), this research was conducted using a longitudinal design so as to capture developmental changes in these three variables and thus provide a better understanding of their developmental trajectories and predictors. Two main issues were examined. Firstly, the aim was to determine whether the evolution of arithmetic skills could be predicted by developmental changes in sensorimotor finger sills. As finger gnosias and FMS were found to be specific predictors of arithmetic development (Asakawa & Sugimura, 2014; Noël, 2005), developmental changes in these two sensorimotor finger skills were expected to predict uniquely the evolution of arithmetic performance. Secondly, the mediating role of finger-use on the possible relationships between sensorimotor finger skills and arithmetic skills was investigated. Given that Butterwoth's (1999) *functionalist hypothesis* suggests that sensorimotor finger skills would support the development of finger-use that would, in turn, support children's arithmetic development, finger-use was expected to mediate the relationship between the developmental changes of sensorimotor finger skills and the evolution of the arithmetic skills.

2 Method

2.1 Participants

Seventy-five French speaking children (40 girls; Mean age = 6.2 ± 0.3 years at the start of the first grade, first measurement time) from ten mainstream primary schools took part in this longitudinal study. They have been taught mathematics according to the official curricula which does not recommend nor discourage finger-use. Parents were asked to complete an anamnestic questionnaire about their child. All except one did not reported any history of learning disabilities, or neurological, developmental and psychiatric disorders. The child whose parents reported motor disabilities have been excluded from the study. The final sample therefore consists of 74 children. Socio-economic status of families, collected with the International Standard Classification of Occupation (ISCO-08; International Labour Organization [ILO], 2008). The occupation of the parent with the highest status was used as an indicator. The ocio-economic status of families was predominantly high, compared with national statistics, with 50 % of parents working as managers or in an intellectual profession, 34% as employee or technician and 16% in the agricultural sector.

The participants were assessed at four time points, in the spring and autumn of the first grade (T1, Mean age = 6.2 ± 0.3 years; T2, Mean age = 6.7 ± 0.3 years) and of the second grade (T3, Mean age = 7.3 ± 0.3 years; T4, Mean age = 7.7 ± 0.3 years; mean interval between two sessions = 5.7 months). Two cohorts of children were enrolled one year apart. The first cohort of children (n=36) was followed from September 2020 to May 2022, while the second cohort (n=35) was followed from September 2021 to May 2023.

The research was approved by the local ethic committee (reference number: 1819-64). Parents of participants gave written informed consent. Each child was informed of the research and consented to participate.

2.2 Measures

Arithmetic. To assess the arithmetic skills, the child was asked to solve problems horizontally presented on a computer screen. The stimuli consisted of 36 items of increasing difficulty (18 additions and 18 subtractions; Table 1), half of which involved a carry or a borrow.

The level of difficulty of each item was determined using a staircase procedure (inspired by Geurten et al., 2021) established through the pre-testing of 30 children enrolled in Kindergarten (n=11, Mean age = 5.2 ± 0.2 years), in first grade (n=10, Mean age = 6.4 ± 0.2 years) or in second grade (n=9, Mean age = 7.3 ± 0.2 years). Prior to the pre-test sessions, the 36 items were classified into three levels of difficulty based on the mathematics curricula for children attending school in French-speaking part of Belgium. Level 1 items consisted of Unit+Unit (U+U) additions without carry, suitable for kindergartners. Level 2 items included Tens-Units+Units (TU+U), TU+TU without carry, U-U and TU-U subtractions without borrow, and U+U, TU+U additions with carry. All these items were suitable for first-graders. Finally, Level 3 items, suitable for second-graders, consisted of TU+TU additions with carry and TU-U subtractions with borrow. During the pre-test sessions, kindergartners were asked to solve Level 1 and Level 2 items, while second-graders were asked to solve Level 2 and Level 3 items. First-graders were divided into two groups: five of them had to solve Level 1 and Level 2 items, the others had to solve Level 2 and Level 3 items. Level 1 items not introduced to second-graders were treated as passed while the Level 3 items not introduced to kindergartners were considered as failed. The final order of items was established according to the average success rates for each item obtained during the pre-test session.

When solving the experimental task, the child was asked to provide their answer orally. The answers as well as the time interval between the presentation of the item and child's response were recorded. In addition, the strategy used to solve each problem (i.e., mental calculation or finger-use) was reported. One point was awarded for each correct answer. The assessment stopped after three consecutive errors. The internal consistency of the task was high with Cronbach's alpha of 0.89.

Table 1: Additive and subtractive problems of the arithmetic task.

1+2=	12+4=	23-4=	16-9=
3+1=	3+8=	42-4=	48-6=
3-1=	7+5=	31-2=	17-8=
4-1=	14-2=	12-5=	42-7=
6-3=	2+23=	38-5=	23+57=
5+3=	5+14=	13-5=	37+29=
9-5=	26-4=	24-9=	9+13=
4+6=	7+16=	38+11=	46+16=
8-4=	25+8=	12+24=	35+23=

Fine motor skills. FMS were assessed through four subtests, three from the Movement Assessment Battery (MABC-2, Henderson et al. 2007) and one timed tapping task.

Visuomotor precision involving unimanual fine motor skills was assessed in the placing pegs subtest. The child was asked to place 12 pegs, as quickly as possible, on a pegboard (i.e., a 12 holes board with four lines of three holes). He was asked to use one hand and manipulate one peg at a time. Both hands were tested one after the other, starting with the dominant hand. The subtest started with a training trial in which the child had to place 6 pegs followed by a test trial in which the child was required to place 12 pegs. The execution time taken to place the 12 pegs was recorded. Two trials were administered with each hand. The best of the two execution times was recorded. The average performance of both hands was taken as the score for the first subtest.

Visuomotor precision involving bimanual coordination was assessed in the threading lace subtest. The child had to thread a lace, as quickly as possible, through board perforated with eight holes. The lace had to be passed through one hole at a time, back and forth between the left and the right sides of the board. Before starting the subtest, a training trial was carried out, during which the child had to thread the lace through four holes. The time taken to pass the lace through the eight holes was reported. The participant had to repeat the subtest twice. The best of the two times was considered.

Graphomotor skills were assessed in the drawing trail subtest in which the participant had to draw a continuous line within a path delimited by two equidistant lines. The child was required to comply with the four following instructions. (1) The line drawn must not cross the boundaries. (2) The pen must not be lifted from the sheet. If it were, the drawing would resume where the pen had been lifted. (3) The line had to be drawn in a single direction. (4) The exercise sheet could not be tilted by more than 45°. A training trial was presented to the child before starting the subtest. An error was counted each time one of the four instructions was broken. Two trials were performed, with the best performance being retained as the score of the subtest.

Finally, the timed tapping subtest was administered to assess the sequential coordination of individual finger movements. The participant had to reproduce as many finger movement sequences as possible in 30 seconds. Four trials were conducted. (1) Tapping on the table following the fingers anatomical position (thumb, index finger, middle finger, ring and pinky finger). The trial was conducted first with the right hand, then with the left hand. (2) Tapping on the table, starting with the left little finger, followed by the fingers of the left and right hands, ending with the right little finger. (3) Tapping on the table, moving one finger out of two. The movement started with the left little finger, followed by the fingers of the left and right hands, ending with the right little finger. (4) Tapping on the table, moving one finger out of two. This last movement consisted of a back-and-forth motion. First, children had to tap the table with the fingers of their left hand, then those of their right. They then repeated the movement with the fingers of the right hand, finishing with those of the left hand. Before each trial, the child was asked to repeat the required movement three times for practice. One point was awarded for each finger movement sequence correctly executed (i.e., when the fingers were mobilized one after other in the correct order). The average performance of both hands was taken as the score of the first trial. The subtest score was the sum of the correctly executed finger sequences over the four trials.

An FMS score had been extracted from the four subtests scores, by applying a Principal Component Analysis (PCA). Results of PCA confirmed that the four subtests reflect a single construct, which accounts for 65% of the total variance across the subtests. An amount of variance of .32, .31, .30 and .30 was respectively extracted from the placing pegs, the threading lace, the drawing trail and the timed tapping subtest.

Finger gnosia. The child was asked to put one hand palm-down, flat on the table with fingers spread out. He was shown a card on which a hand with colored fingers was drawn. His hand was occulted with a cardboard and, out of the participant's view, the experimenter touched the middle phalange of one finger. Then, the cardboard was removed and the child was asked to indicate, according to the card, the color of the finger that had been touched. A total of ten trials were performed for each hand. The five first trials consisted of one touch, while the five last trial consisted of two successive touches. One point was awarded when the child correctly reported the finger(s) touched. For two-touch trials, one extra point was awarded when the fingers were stated in the order in which they were touched. The sum of the points was taken as the score for the task. The highest score was 30 points. The internal consistency of the task was acceptable with a Cronbach's alpha of 0.69.

2.3 Procedure

Children were assessed individually by the first author or a trained student assistant, in a quiet room at their school. The same protocol was administered at each time point during an assessment session lasting approximately 40 minutes. The order of the measurements was counterbalanced across the children.

2.4 Analyses

The results were analyzed in two stages. Firstly, the predictive value of changes of FMS and finger-gnosia on the arithmetic skills development was examined to determine predictors of arithmetic development. After correlations were made, the data were submitted to latent growth modeling (LGM), using Mplus 5.21 software (Muthén & Muthén, 2008). The developmental trajectories of each of the three measures (i.e. arithmetic, FMS, finger gnosia) were first examined according to a linear LGM for a continuous outcome. A LGM with time-varying covariates was then implemented to identify significant predictors of arithmetic skill development.

Developmental trajectories had to reflect a significant change over time to be taken into account in the LGM with time-varying covariates.

Secondly, finger-use, defined as the ratio of the number of items solved with fingers to the number of items processed by the child in the arithmetic task, was taken into consideration. After examining correlations, a linear growth model was conducted to investigate the developmental trajectory of finger-use efficiency, with the aim of running linear growth model with time-varying covariates examining its predictive value on the arithmetic skills development, as well as its longitudinal mediating effect on possible relationships between sensorimotor finger skills and arithmetic abilities.

3 Results

3.1 Predictive value of changes in sensorimotor finger skills on arithmetic development.

3.1.1 Correlations

The table 2 reports the Pearson's correlations between arithmetic, FMS and finger-gnosia at the four measurement times (i.e., Autumn and spring and of the first grade (T1 and T2) and of the second grade (T3 and T4)). Children's arithmetic skills at T3 and T4 were strongly related to their abilities at the previous measurement time (T2 x T3, p<.001; T3 x T4, p<.001). At each time points, FMS and arithmetic skills were weakly correlated (from r=.09 to r=.17), the effects were not significant. Arithmetic skills assessed at later times were also found to be unrelated to the FMS assessed at time T (from r=.11 to r=.21). Finger gnosia were moderately related to arithmetic skills at T2 (p<.001), T3 (p<.001) and T4 (p=.003). A significant correlation was reported between finger gnosia at T1 and arithmetic skill at T3 (p=.001).

Table 2. Pearson's correlation between arithmetic, FSM and finger-gnosis at the four measurement times.

	1	2	3	4	5	6	7	8	9	10	11
1. Arith. T1	—										
2. Arith. T2	.22	—									
3. Arith. T3	.33**	.46***	—								
4. Arith. T4	.08	.18	.46***	—							
5. FMS T1	.09	.11	.21	.23	—						
6. FMS T2	.18	.10	.20	.13	.87***	—					
7. FMS T3	.15	-.09	.15	.06	.66***	.67***	—				
8. FMS T4	.03	-.12	.26*	.17	.42***	.37**	.78***	—			
9. Finger gnosia T1	.05	.33**	.38**	.14	.08	.15	.16	.13	—		
10. Finger gnosia T2	-.03	.41***	.42***	.21	.15	.29*	.15	.11	.50***	—	
15. Finger gnosia T3	.34**	.19	.49***	.24	.33**	.26*	.20	.23	.39**	.22	—
16. Finger gnosia T4	.30*	.19	.45***	.37**	.37**	.36**	.25*	.20	0.28*	.39**	.66***

Note. FMS: Fine motor skills, T: Time.

* *p*<.05, ** *p*<.01, *** *p*<.001

3.1.2 Trajectory of change of arithmetic, FMS and finger gnosia

Before conducting the LGM with time-variant covariates, the trajectory of change for each variable, defined as the average change, was examined in linear LGM.

The parameter estimates for arithmetic LGM showed that, on average, children correctly solved 2.89 problems at T1 (p<.001). Between T1 and T4, arithmetic skills increased gradually (+15.24 points, Table 3; p<.001), with an average improvement of 4.9 points between two measurement times. The correlation between initial value and rate of change was -.16 (p=.59), indicating that the children's improvement in arithmetic between the first and the second grades was independent of their skills at T1. The variance of the initial value did not statically differ from 0 (Estimate = 6.17, p=.28), suggesting that, at T1, there were no notable individual differences in arithmetic skills among the children. On the other and, the variance of rate of change (Estimate = 3.87, p=.006) significantly differs from 0, suggesting heterogeneous progress among children.

The linear LGM parameter estimates for FMS showed that, at T1, children had an average score of -.43 points (p<.001). Between T1 and T4, FMS increased gradually (+1.3 points, Table 3; p<.001), with an average improvement of .40 points between two sessions. The correlation between FMS initial value and rate of change was significant -.82 (p<.001), indicating that higher initial values of FMS were associated with a slower rate of increase. The variance of the initial value (Estimate=.98; p=.004), and of the rate of change (Estimate = .07, p=.001) significantly differ from 0, confirming that individual differences existed in FMS and changes therein up to the end of the grade 2.

Finally, the parameter estimates of finger gnosia linear LGM showed that, at the first measurement time, children had an average score of 20.84 points (p<.001). Finger gnosia increased gradually between T1 and T4 (+2.3 points, Table 3; p=.006), with an average improvement of .67 points between two sessions. The correlation between finger gnosia initial value and rate of change was significant -.45 (p=.007), indicating that higher initial values of finger gnosia were associated with a slower rate of increase. The variance of the initial value (Estimate=14.83; $p<.001$), and of the rate of change (Estimate = .67, $p=.01$) differ significantly from 0, confirming that individual differences existed in finger gnosia and changes therein up to the end of the grade 2.

In summary, arithmetic skills at the two assessments in grade 2 (T3 and T4) was directly related to skills at the previous assessment sessions. When all measurement times were taken into account, arithmetic skills improved significantly between the beginning of grade 1 and the end of grade 2. This improvement was not related to children's arithmetic skills upon entering elementary school. Similar to arithmetic skills, FMS and finger gnosia improved significantly between the beginning of grade 1 and the end of grade 2.

Table 3. Descriptive statistics of arithmetic, FMS and finger-gnosia.

	N	Mean score (SD)	Range	
			Min.	Max.
Arithmetic				
Grade 1- autumn	68	2.96 (3.28)	0.0	17.0
Grade 1- spring	68	6.69 (6.10)	1.0	27.0
Grade 2 - autumn	67	12.50 (6.37)	0.0	31.0
Grade 2 - spring	64	18.20 (8.78)	1.0	33.0
FMS				
Grade 1- autumn	70	-0.41 (0.99)	-4.8	1.0
Grade 1- spring	69	-0.22 (0.88)	-4.6	0.8
Grade 2 - autumn	67	0.50 (0.61)	-1.6	1.5
Grade 2 - spring	65	0.81 (0.61)	-1.0	2.1
Finger-gnosia				
Grade 1- autumn	71	20.50 (5.30)	9.0	30.0
Grade 1- spring	70	22.00 (4.70)	12.0	30.0
Grade 2 - autumn	67	21.80 (5.22)	5.0	30.0
Grade 2 - spring	65	22.80 (5.03)	11.0	30.0

3.1.3 Latent Growth Model with time-variant covariates

A linear LGM with time-variant covariates was conducted to examined the predictive power of initial value and changes in FMS and finger-gnosia on the arithmetic skills development. According to this model, the initial value of FMS significantly predicted neither the initial value (standardized β=.06, S.E=.21, p=.78) nor the rate of change in arithmetic skills (standardized β=.45, S.E=.33, p=.18). Nor did improvement in FMS over time predict the arithmetic skills development (standardized β=.13, S.E=.30, p=.66).

A second linear LGM with finger-gnosia as time-variant covariates was conducted. The initial value of finger gnosia was a significant predictor of the initial value (standardized β=.32, S.E=.16, p=.05) and of the rate of change (standardized β=.72, S.E= .16, p<.001) of arithmetic skills. The slope of the finger gnosia latent variable was not significantly associated with the slope of the arithmetic development. The R-square analysis showed that, together, the initial value and the rate of change of finger gnosia explain 43% of the development of arithmetic skills between the beginning of grade 1 and the end of grade 2, which represents a significantly large explanatory part (p<.02).

To sum up, FMS were not associated with the arithmetic development and of its initial status. In contrast, the initial value of arithmetic skills was predicted by the initial value of finger gnosia. Taken together, the initial value and the rate of change of finger gnosia appeared to be a key predictor of arithmetic development.

3.2 Longitudinal mediating effect of finger-use

3.2.1 Correlations

Children's finger-use at T3 and T4 were strongly related to their abilities at the previous measurement time (T2 x T3, r=.65, p<.001; T3 x T4, r=.67, p<.001). At no time of measurement, finger-use was related to arithmetic performance (from r=-.11 to r=.07). Nor did the finger-use at a given time predict arithmetic performance at later time (from r=-.16 to r=.14; except for T2xT4, r=-.31, p=.01). At no stage of development was the finger-use to be related to FMS (from r=-.14 to r=.05). In contrast, finger-use and finger gnosia were negatively correlated at T3 (*r*=-.43, *p*<.001) and at T4 (*r*=-.42, *p*<.001). Finger-use at T2 and T3 negatively predicted finger gnosia at T4 (T2xT4, *r*=-.33, *p*=.01; T3xT4, *r*=-46, *p*<.001).

3.2.2 Latent growth models

The parameter estimates for the finger-use LGM showed that during the first measurement session, children solved an average of 21% of the arithmetic problems using finger-use strategies (*p*<0.001). Between T1 and T4, finger use efficiency decrease by less than 6%, which does not reflect a significant decrease over time (Estimate= .005, *p*=.48). The dispersion of the rate of change (Estimate = .002, *p*=.01) was significant, indicating that there was individual differences in the evolution of finger-use between the beginning of the grade 1 and the end of the grade 2.

As the finger-use measure was shown to be stable over time, conducting multivariate analyses to examine its predictive value on the development of children's arithmetic skills as well as its mediating role on the relationship between sensorimotor finger skills and arithmetic abilities was not suitable.

4 Discussion

The aim of this study was to test the *functionalist* hypothesis in the development of arithmetic skills. Primary school children were assessed four times, every six months, between autumn and spring of the first (T1 and T2) and of the second grade (T3 and T4). The developmental trajectories of FMS, finger gnosia, finger-use and arithmetic skills were examined to determine whether (1), the evolution of arithmetic skills could be predicted by the developmental changes in FMS and finger gnosia and whether (2) the developmental changes in FMS and finger gnoais could support the development of arithmetic skills through the finger-use.

Firstly, the results showed that arithmetic skills improved between the first and the second grade. Children displayed a range of developmental trajectories. The lack of correlation between the initial value and the rate of change in the linear LGM indicated that children’s arithmetic skills at the beginning of first grade couldn’t account for these individual differences. Indeed, at the first measurement time, arithmetic skills were uniformly poor among all children, as the majority (72%) struggle to solve more than two of the 33 calculations given in the task.

Interestingly, finger gnosia were shown to strongly predict the development of arithmetic skills. Finger gnosia at the beginning of primary school and their evolution between the four measurement times explained 43% of the development of arithmetic skills. These results provided evidence that finger gnosia were a key predictor in the development of arithmetic skills. This was consistent with the finding of Noël's longitudinal investigation (2005), which found that finger gnosia at the end of kindergarten strongly predicted arithmetic skills at the end of primary school. At first glance, once might be tempted to explain the current results by adopting a functional approach. To develop arithmetic skills, children must learn to count efficiently on their fingers. To do this, each finger must be identified as a distinct entity (reflecting good finger gnosia), so that it can be mobilized in an appropriate movement to accompany verbal counting or enable the child to present numbers with fingers patterns (e.g., by raising the thumb, index and middle fingers to represent 3). Here, however, this explanation seemed unlikely. Indeed, at no time during the longitudinal follow-up were finger gnosia and finger-use significantly correlated. Furthermore, no change in finger-use over time could be demonstrated between the beginning of the first grade and the end of the second grade, preventing the application of multivariate latent models. These results were in line with Asakawa and Sugimura (2022) who showed a lack of correlation between finger gnosia and finger-use in 5-year-old children, once age and working memory were controlled. Overall, the current results demonstrate that between first and second grade, finger-use during calculation is not supported by finger gnosia, ruling out the possibility that finger gnosia may contribute to the development of arithmetic skills, through the learning of finger-based strategies.

An alternative hypothesis to explain the current results could be that finger gnosia would promote the development of arithmetic skills through finger patterns. Conforming to counting habits, the canonical finger patterns are processed quickly and accurately by children (Noël, 2005; Lafay et al., 2013). They provide a direct access to the semantics of number, making them a numerical symbol (Di Luca &

Pesenti, 2008) in the same way than number-words or Arabic numbers. Mastery of finger patterns at the end of kindergarten, like that of structured dot patterns, has also been shown to be a unique predictor of the development of arithmetic skills in the middle of first grade (Kreilinger et al., 2021). Their structured nature could help children refine their knowledge of quantities by facilitating the comprehension of number composition and decomposition (Kreilinger et al., 2021; Kullberg & Björklund, 2020), an important skill in the development of arithmetic. When solving a calculation, children could thus rely on their knowledge of the sub-base five of their hands to easily decompose the number 8 into 5+3. Efficient finger gnosia involves recognizing each finger and being able to situate them in relation to each other. As these skills are also required to accurately identify finger patterns, one might assume that the development of finger gnosia could contribute to learning these patterns. In 2020, in their longitudinal investigation, Van Rinsvald et al. showed that finger gnosia were correlated with finger pattern recognition in 5-year-olds. Nevertheless, their attempt to prove that finger gnosia could predict symbolic numerical processing (assessed by a task of placing arabic numbers on unscaled lines) through the finger patterns. As finger gnosia appear to be mature by age 10 (Chinello et al., 2013), the authors suggested that the triadic relationship between finger gnosia/finger patterns and numerical processing might emerge later in development, during the primary school years. In the case of the present study, this could explain one of the mechanisms by which finger gnosia predict the evolution of arithmetic skills between the beginning of the first grade and the end of the second grade. However, this hypothesis needs to be tested in future researches.

In the current study, the predictive value of FMS on arithmetic development was also investigated. Unexpectedly, the present results showed that neither the initial value of FMS nor its evolution over the four measurement times were significant predictors of arithmetic skill development. This finding was surprising, as they differed from those of Asakawa and Sugimura (2014), who found that FMS at age 4 strongly predicted the arithmetic development two years later. This discrepancy could be explained by the period at which the follow-ups were conducted. In contrast to the children followed in the present research, Asakawa and Sugimura (2014) worked with 4-year-olds who were still in preschool. During this period, fingers play an important role in early numerical learning. Indeed, when they don't know number-words, preschoolers preferentially use their fingers to communicate quantities (Gunderson et al., 2015). Moreover, finger-use facilitates the learning of the cardinal value of new number-words (Gibson et al., 2019; Orrantia et al., 2022) probably by creating bridges between quantities and verbal symbols (Andres et al., 2008; Di Luca & Pesenti, 2008; Krinzinger, 2011). In the current study, the participants were older and made minimal use of their fingers to solve the arithmetic task. In fact, during the four measurement times, finger-based strategies were used in the solvation of 12 to 15% of the total calculations processed. As early as the first year of primary school, the children exhibited a strong preference for mental calculation strategies (i.e., retrieval of arithmetic facts, additive decompositions) certainly promoted by Belgian teachers for instruction of arithmetic. The limited finger-use during the follow-up period could explain why the development of FMS failed to predict the development of arithmetic skills. Another explanatory factor could stem from the nature of the tasks used here to assess FMS. These were mainly object manipulation tasks (i.e., placing pegs, threading lace) or drawing tasks (i.e., drawing trail), which involved not only motor components but also graphomotor and visuomotor abilities. The multi-determined nature of these tasks could then make them less sensitive in capturing the motor components involved in finger-use, which could explain why FMS failed to predict the development of arithmetic skills.

To sum up, this research is the first to investigate the triadic relationship between FMS and finger gnosia /finger-use and arithmetic skills from a developmental perspective. Finger gnosia at the beginning of primary school and their evolution between the four measurement times explained a strong part of the development of arithmetic skills. There was no evidence that this relationship was underpinned by finger-use. The evolution of FMS did not predict the development of arithmetic skills. If we are to gain a better understanding of the mechanisms underlying the relationship between FMS and arithmetic skills, future studies could be conducted preferentially in preschoolers aged 3-5 years. At this age, the fingers supports learning the cardinal value of number-words, an essential skill to understand the notions of addition (Sarnecka & Carey, 2008; Sella & Lucangeli, 2020) on which arithmetical reasoning is rooted. FMS could then be assessed by tasks capturing only the motor components involved in the numerical gestures used by children of this age. Finger configuration imitation tasks could be good candidates for such an evaluation.

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Chapter 5 - Contribution of finger gnosia and fine motor skills to early numerical and arithmetic abilities: New insights from 3D motion analyses.

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Abstract:

Finger gnosia and fine motor skills (FMS) are assumed to play a key role in the development of arithmetic abilities, but their contribution to early numerical skills (i.e., enumeration skills and cardinality) has received little attention so far. The purpose of this study was to investigate the predictive value of finger gnosia and FMS to enumeration, cardinal, and arithmetical abilities and how these different dimensions contribute to arithmetic development. Three- to five-year-old preschoolers were asked to perform tasks assessing enumeration, cardinality, and early arithmetic, as well as finger gnosia and FMS. FMS, involving either static or dynamic fine finger movement, were examined using a 3D motion analyses. Using hierarchical regression, FMS were found to be the best predictor of both cardinality and early arithmetic skills, while finger gnosia did not predict the additional variance of arithmetic performance when FMS and age were considered in the regression model. Moreover, neither finger gnosia nor FMS were significant predictors of enumeration. Mediation analyses indicated that knowledge of the cardinal principle fully mediates the relationship between FMS and arithmetic skills, suggesting that FMS contribute to cardinal principle knowledge development, which would be a gateway to more complex arithmetical processing.

Keywords:

Early numerical skills, cardinality, enumeration, arithmetic, finger gnosia, fine motor skills, 3D motion analyses.

1 Introduction

The preschool and early school years constitute a critical period for children's academic development. In mathematics, early numerical skills learned in this developmental window play a key role in predicting children's later mathematics outcomes (Jordan et al., 2009; Nguyen et al., 2016; Watts et al., 2014), even going so far as to predict their enrolment in higher education (Davis-Kean et al., 2022). Over the past 15 years, there has been increasing interest in the cognitive factors underlying the development of numerical skills.

Early numerical skills gradually develop throughout childhood. Between the age of two and four, children begin to recite the sequence of number words by rote (Fuson et al., 1982; Wynn, 1992) and learn to determine the exact number of objects in a set, establishing a one-to-one correspondence between number words and items to be counted (Gelman & Gallistel, 1978). During preschool years, counting skills improve to achieve increasing flexibility in the recitation of the verbal number sequence as well as a more in-depth understanding of the cardinal meaning of number words. Commonly assessed using the 'Give-a-Number' task (i.e., children asked to give a puppet a specific number of objects; Wynn, 1990, 1992), the acquisition of the cardinal meaning of number words is a long process (i.e., lasting more than a year) during which children move, for one number at a time, through different number-knowledge levels (Le Corre et al., 2006; Le Corre & Carey, 2007; Rousselle & Vossius, 2021; Sarnecka & Gelman, 2004; Wynn, 1990, 1992).

In their developmental model, Krajewski and Schneider (2009) identify recitation, enumeration skills, and cardinal principle knowledge as precursors to the development of arithmetic skills. In this respect, some recent studies have investigated how their acquisition by preschoolers can predict later arithmetic skills. Longitudinal investigations provide evidence that advanced counting (i.e., conceptual elaboration of the verbal number sequence) at age five is a strong predictor of arithmetic skills two years later (Lê & Noël, 2021). Likewise, enumeration abilities (i.e., subitizing and/or counting in dot enumeration tasks) assessed at age five were found to predict fluency in addition tasks five to seven years later (Bartelet et al., 2014; Major et al., 2017). Cardinal principle knowledge (i.e., ‘Give-a-Number’ task) also appeared to be a strong predictor of arithmetic development since it has been shown that children’s understanding of the cardinal value of number words at age four predicts performance in addition four months later (Scalise & Ramani, 2021) as well as the sophistication of arithmetic solving strategies three years later (Chu et al., 2018). Taken together, this evidence suggests that enumeration skills and cardinal principle knowledge play a key role for later arithmetic development.

A growing body of research suggests that the development of mathematical concepts is deeply rooted in children's sensorimotor experiences, a hypothesis that fits into the broader theory of embodied cognition. In the context of mathematical development, this theoretical framework posits that numerical symbols and concepts become meaningful when embedded in bodily experiences (Barsalou, 2008; Moeller et al., 2012; see Andres & Pessenti, 2015, for a review). In this respect, fingers have a privileged status for the development of numerical concepts. They provide an embodied representation of different core numerical properties (cardinality, ordinality, one-to-one correspondence, abstraction; Crollen et al., 2011) which support the internalization of abstract concepts through the multimodal (visual, motor, and proprioceptive) association between numbers and fingers (Butterworth, 1999; Fuson et al., 1982; Lakoff & Nunez, 2000). Concrete and always available, they are the ideal tool for young children to begin learning numbers.

During class activities, preschoolers often use their fingers to solve various types of numerical problems (Gordon et al., 2019; Noël, 2005; Reeve & Humberstone, 2011). As an extension of the developmental model of Krajewski and Schneider (2009), Roesch and Moeller (2015) have clarified how fingers presumably contribute to early numerical and arithmetical acquisitions. Specifically, they assumed that fingers not only help children to visualize and combine quantities in solving arithmetic problems, but also support early numerical development including the acquisition of the verbal number sequence, counting skills, and cardinal concepts. Consistent with their proposal, fingers proved to be a very effective tool in solving problems from the age of five (Baroody, 1987; Dupont-Boime & Thevenot, 2018; Jordan et al., 2008), laying ground for the development of finger-based solving strategies. Furthermore, combining *finger-counting* that provides ordinal finger-based numerical representations (i.e., raising and counting fingers one at a time) with *cardinal number gestures* that provide a cardinal finger-based numerical representation (i.e., using a finger pattern to represent the cardinal of a set)[4] turned out to be more effective than strategies involving finger-counting only (Björklund et al., 2019). Critically, what makes the fingers a powerful tool when solving arithmetic tasks in the early years would depend on children's ability to recognize the meaning of cardinal number gestures, as well as on their knowledge of the part-whole relationships between numbers that are intrinsically embedded in fingers (Kullberg & Björklund, 2020).

While the role of fingers in the development of arithmetic in preschoolers is quite clear, little is known about their possible role in the acquisition of cardinal concepts. As cardinal number gestures provide an iconic representation of numbers (i.e., each raised finger can be mapped to an item of the set), some authors suggest that four-year-old children learn the cardinal meaning of number gestures earlier than number words (Gibson et al., 2019; Gunderson et al., 2015). In a randomized controlled trial, training cardinal principle knowledge through counting and labelling activities in three-year-old children was found to be more effective when enriched with cardinal number gestures (Orrantia et al., 2022). Conversely, other authors have claimed that children between the ages of two and five are not sensitive to the iconicity of cardinal number gestures (Nicoladis et al., 2018) and consider that this medium provided no advantage in the acquisition of cardinal concepts (Nicoladis et al., 2010). Thus, for now, the contribution of fingers to cardinal understanding is still a matter of debate.

Recent investigations have been conducted to determine which sensorimotor finger skills promote early numerical processing development to gain further insight into the mechanism involved. To date, the sensorimotor finger skills identified as related to numerical development fall into two different categories. The first to be identified is

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[4] Also known as finger-montring when cardinal number gestures are used to show numerosities *to other people* using fingers (Crollen et al., 2011; Di Luca & Pesenti, 2008; Fischer et al., 2022).

finger gnosia, which refers to the representation of finger positions on one's own hand (Noël, 2005; Strauss & Werner, 1938). This component, usually assessed through tactile stimulation, was found to predict numerical system development (i.e., transcoding, ordinality, and place value in six-year-olds; Penner-Wilger et al., 2007) and arithmetic development in typically developing children between five to twelve years (Newman, 2016; Noël, 2005; Wasner et al., 2016) as well as in children with mathematical learning disabilities (Costa et al., 2011). More recently, the motor component, captured in tasks assessing fine motor skills (i.e., the ability to move fingers differentially) has attracted attention. Fine motor skills (FMS) were found to be directly (Fischer et al., 2022; Gashaj et al., 2019; Penner-Wilger et al., 2007) and indirectly related to number processing through ordinal and cardinal finger-based numerical representations (respectively, finger-counting (Fischer et al., 2018, 2020, 2022; Suggate et al., 2017) and cardinal number gestures (Fischer et al., 2020; Suggate et al., 2017)). A positive influence of FMS training on finger gnosia and arithmetic skills has also been demonstrated in six-year-old children (Asakawa et al., 2019; Gracia-Bafalluy & Noël, 2008; but see Schild et al., 2020, for conflicting results) clarifying the causal mechanisms underpinning this relationship.

In short, a number of publications suggest that finger gnosia and FMS somehow contribute to numerical and arithmetic development. These associations make sense in the functionalist hypothesis, which assumes that sensorimotor finger skills support the development of ordinal (i.e., finger-counting) and cardinal (i.e., cardinal number gesture) finger-based numerical representations, which in turn promote the development of verbal cardinal knowledge and arithmetic processing (Brissiaud, 2005; Butterworth, 1999). Under this assumption, some specific dimension of sensorimotor finger skills should be more determinant to the development of finger-based numerical representation and, by extension, to development of counting, cardinality, and arithmetic. However, the nature of these specific dimensions remains unclear. The vast majority of tasks used to assess FMS in children and adolescents involve object manipulation (e.g., pegboard, threading beads, posting coins, etc.) or drawing (e.g., figure copying), resulting in tasks that are often multi-determined, requiring not only FMS but also visual-spatial or grapho-motor abilities (see Neveu et al., 2023, and Barrocas et al., 2020, for a discussion about the tasks). In this respect, Barrocas et al. (2020) stressed the importance of isolating FMS from visual components to better understand their involvement in numerical development. Only two studies have been conducted in this direction, using finger tapping tasks (Fischer et al., 2022; Penner-Wilger et al., 2007) that have the advantage of involving only selective finger movement (i.e., no visual-spatial or grapho-motor abilities) but with limited demand in terms of fine motor precision. In its current state, such a task remains insufficient to specifically identify the FMS components that bring added value to the understanding of numerical concepts.

The purpose of the present study is to go one step further to understand the relationship between sensorimotor finger skills (i.e., finger gnosia and FMS) and early numerical abilities (i.e., enumeration, cardinal principle knowledge, and arithmetic skills), focusing on FMS that are closely related to the motor processes involved in ordinal (i.e., finger counting) and cardinal (i.e., number gestures) finger-based representations in typically developing young children. Two main categories of FMS were thus considered here: (1) the *static FMS* that enable the positioning of fingers in space to adopt finger configurations (i.e., a key component of cardinal finger gestures), and (2) the *dynamic FMS* that allow the sequential coordination of individual finger movements (i.e., a key component of finger-counting). To overcome the limit of paper-and-pencil measures that provide only dichotomous outcomes (i.e., correct or incorrect positioning), FMS were examined using a three-dimensional (3D) motion technique to provide fine-grained continuous measurement of finger movement quality. 3D motion analysis is a non-invasive method of tracking human movements and is used to measure the position and movement velocities of specific body segments.

The present study addresses two main issues in relation to the functionalist hypothesis: (1) the predictive value of sensorimotor finger skills in enumeration, cardinal, and arithmetical abilities and (2) the mediating role of early numerical skills (enumeration and cardinality) in the possible relation between sensorimotor finger skills and arithmetical development. With regard to the first issue and in line with previous findings (e.g., Noël, 2005; Penner-Wilger et al., 2007), finger gnosia was expected to predict arithmetic skills but its possible contribution cardinal principle knowledge has, to our knowledge, not been examined so far. As findings regarding the contribution of finger gnosia to enumeration skills are contradictory (Long et al., 2016; Malone et al., 2020), no expectation has been advanced here. Moreover, considering their essential role for cardinal and ordinal finger-based solving strategies involved in early arithmetic, *static* and *dynamic FMS* should be significant predictors of arithmetic skills. In addition, as a key component of cardinal number gestures, static FMS specifically were expected to predict verbal cardinal knowledge. By contrast, enumeration skills involve either subitizing for small numerosities or single finger pointing in counting routines for numerosities larger than three. As these processes involve no (complex) finger movement, they have little to do with the finger gnosia and motor processes involved in finger-counting and cardinal finger gestures. As such, *static* or *dynamic FMS* and finger gnosia were not expected to predict enumeration abilities, as assessed in the current experiment. With regard to the second issue, depending on the results of the first set of analysis, the predictive relationship between sensorimotor finger skills and arithmetic will be further explored through mediation analysis to determine whether early numerical abilities could act as mediators in this relationship.

2 Method

2.1 Participants

Thirty-four typically developing French-speaking three- to five-year-old preschoolers (M=51.9±7.7 months, range=39-63 months, 16 girls) participated in the experiment. Parents were asked to complete an anamnestic questionnaire about their children. They reported no history of learning disabilities, or neurological, developmental, or psychiatric disorders. Socio-economic status of the families, collected with the International Standard Classification of Occupation (ISCO-08; International Labour Organization [ILO], 2008), was predominantly high, with 63.7% of parents reporting working as managers or in an intellectual profession, 33.3% as employees or technicians, and 3% in the agricultural sector.

The research was approved by the local ethics committee. The parents of participants gave written informed consent. Each child was informed of the research and consented to participate.

2.2 Tasks

2.2.1 Early mathematical skills.

Four tasks were used to assess early mathematical skills.

Verbal number sequence. Knowledge of the verbal number sequence was assessed in a recitation task in which the child was asked to count aloud as far as possible (until maximum 20). If necessary, the experimenter could initiate the sequence to prompt recitation (one, two…). The task was performed twice to identify the stable and the conventional part of the verbal number sequence defined as the longest part the child could recite correctly twice (Fuson et al., 1982). Participants were requested to solve the task to ensure that their ability to process the cardinal task was not limited by their knowledge of the verbal number sequence.

Enumeration. To assess enumeration skills, children were shown pictures with sets of randomly arranged black dots on a grey background. The child was asked to say *how many dots were present in all of the picture.* If the child gave an incorrect answer without having counted verbally, they were explicitly asked to count and to say how many dots were present. The stimuli consisted of sets of one to eight dots for a total of eight trials (i.e., three numerosities in the subitizing range and five numerosities in the counting range). The items were presented in a pseudo-random order, with consecutive numbers never presented in succession. One point was given for each correct cardinal response (maximum score=8) but the trial was scored 0 if the child recounted or gave an incorrect cardinal response.

Give-a-Number. Cardinal principle knowledge was assessed using the *Give-a-Number* task (Give-N task) (Le Corre & Carey, 2007; Wynn, 1990). A set of fifteen penguin figurines was presented to the child who was asked to place *n* penguins on a cardboard ice floe placed in front of him. The numerosity of the set was given verbally. If the child placed the correct number of penguins on the cardboard, one point was given and a set of *n*+1 was requested on the next trial. In case of failure, no point was given and a set of *n*-1 figurines was requested on the next trial. When the child used counting to determine the numerosity of the set, one counting imprecision error was accepted and a response of *n*±1 was considered as correct. Unlike Wynn (1990), who limited the task to number words up to six, children could be asked to give up to ten items to get a broader view of how they generalize cardinal knowledge to large number words. The task was stopped when the child succeeded twice for the numerosity *n* and failed twice for the numerosity *n*+1. The highest numerosity was considered as the child's cardinal knowledge level (maximum score=10).

Early arithmetic. Early arithmetical skills were examined using the pictorial additive fluency task adapted from Noël (2009). Children were asked to solve as many word problems as possible (e.g., *"In this cage, there are two birds. If another bird enters in the cage, how many will there be in total?"*) in a limited time (150 seconds). For each item, children were presented with a picture of the first operand. Tokens were provided as concrete support to solve the problem, if needed. Items consisted of ten single-digit additions of increasing difficulty (i.e.,1+1, 2+2, 2+1, 3+3, 3+2, 4+3, 4+4, 5+5, 5+4, 6+5). Half of them were doubles, the last one involved a carry. One point was given for each correct answer (maximum score=10). When all problems were solved within the time limit, one bonus point was given for each interval of five seconds saved.

2.2.2 Sensorimotor finger skills

Finger gnosia were assessed using behavioural measures while static and dynamic FMS were assessed using behavioural measures supplemented by 3D motion analysis, which provides fine-grained measurement of FMS.

Finger gnosia. Finger gnosia were tested in a task adapted from Noël (2005). The child was asked to put one hand, palm down, flat on the table with fingers spread out.

The hand was occluded with a cardboard screen and, out of the child's view, the experimenter touched the middle phalanx of a single finger. Then, the cardboard was removed and the child was asked to indicate, with the other hand, the finger that had been touched. Five trials were administered for each hand (i.e., each of the fingers was touched once) starting with the child's preferred hand. One point was given for each correct response (maximum score=10).

Static FMS. To investigate the static FMS, the child was asked to reproduce, with their preferred hand, finger configurations shown by the experimenter. Each finger pattern had to be held for at least four seconds to record the position. Of the ten trials administered, six depicted numerical finger configurations (i.e., fingers placed in a standard position to represent numbers; e.g., thumb, index, and middle finger raised up, Figure 1) while the remaining four presented non numerical finger configurations (e.g., touch the thumb with the index while raising the middle, ring, and little fingers, Figure 1). One point was given for each finger configuration correctly reproduced (maximum score=10).

Dynamic FMS. To assess dynamic FMS, the child had to reproduce, with their dominant hand, an ordered sequence of finger movements shown by the experimenter. Before each trial, a blank test was conducted to ensure that the equipment did not interfere with the gesture. Three trials were conducted (Figure 1): (1) raising fingers one at a time, following finger anatomical position starting with the thumb, then index, middle, ring, and finally the little finger, (2) tapping each finger, one at a time, on the table in the order of finger anatomical position starting with the thumb, (3) joining the thumb with each other finger of the hand, one at a time, starting with the index, then the middle, ring, and finally the little finger. To be credited as correct, a sequence must be executed in the correct order. One point was given for each ordered sequence of finger movements correctly reproduced (maximum score=3).

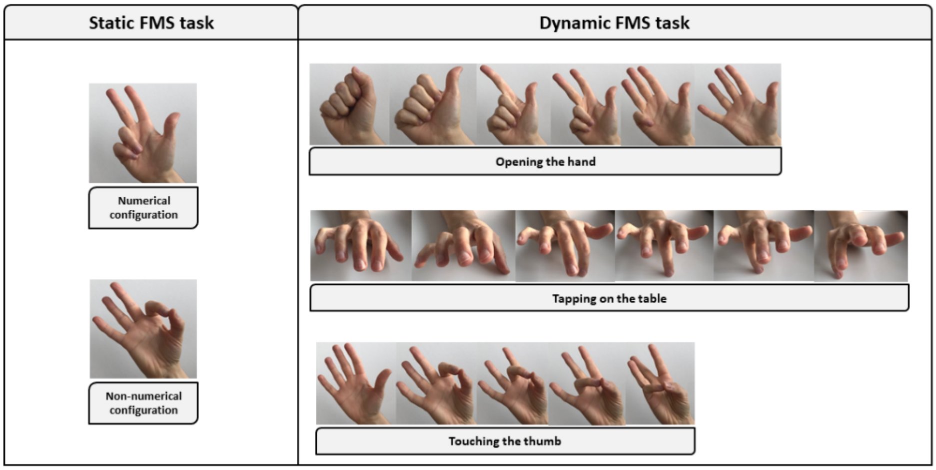


Figure 1: Finger configurations and ordered finger movements showed during the static and dynamic finger gestures tasks.

2.3 3D motion acquisitions and processing

Data acquisition. Four units of a Codamotion 3D optoelectronic system (Charnwood Dynamics Ltd, UK) were used to localize, with millimeter accuracy (Schwartz et al., 2015), twelve 3D markers placed on the child's dominant hand (i.e., one on the proximal and distal phalanx of each finger and one on the distal parts of the first and fifth metacarpals). Acquisitions were performed at a frequency of 200 Hz.

Data processing. Static and dynamic FMS indexes, reflecting the child's fine motor development, were calculated. To determine the static FMS index, a 3D reference hand was first estimated from acquisitions conducted with 21 typically developing children in primary school (M=10.79±0.59 years, 13 girls) for the static FMS task. The 3D reference hand was constructed through a three-step superimposition procedure (Figure 2) (Decker et al., 2007). First, all similar 3D finger configurations were superimposed by a translation of their barycentre. Then, the sizes of the children's 3D finger configurations were standardized so that they could be compared.

The standardization was performed thanks to an estimation of the hand size using the following equation:

$$Hand\ size = \frac{1}{N}\sum_{i}^{N} \|barycenter - M_i\|$$

Barycenter : 3D position of barycenter the makers placed on the hand
N : population size
M_i: 3D position of the i^{th} marker

Finally, a 3D rotation was performed for each 3D finger configuration using a robust iterative closest point procedure (Cresson et al. 2005; Schwartz, 2009). The reference hand was finally defined as the average position of all superimposed hands. A static FMS index was calculated, for each child, as the average distance of each marker placed on their hand and its counterpart on the reference hand. Accordingly, a smaller index indicated a closer distance to the reference hand, with an index of 0 representing a perfect match between the hand configuration and the reference hand.

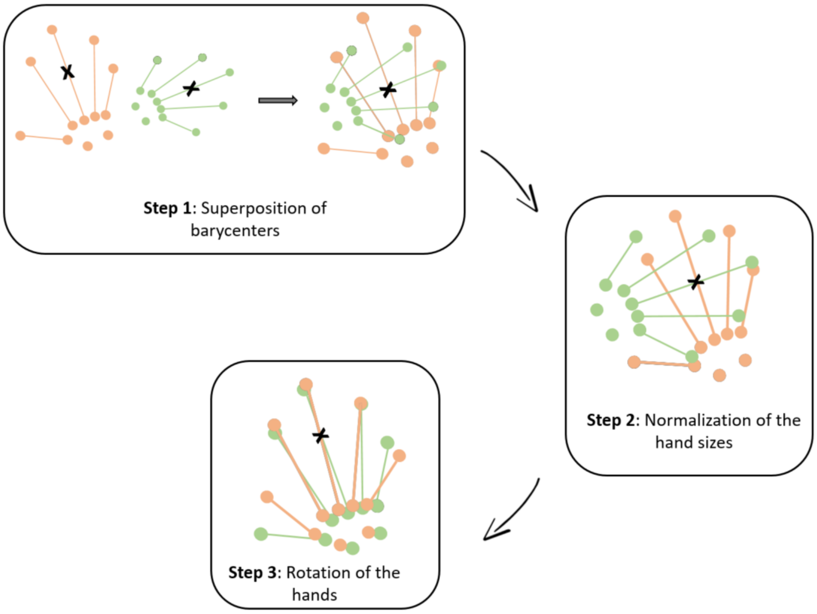


Figure 2: Three-step superimposition procedure. Each circle represents one marker at the surface of the hand.

For each participant, the time intervals between consecutive final finger positions were calculated (e.g., time intervals between consecutive finger/thumb contacts) to determine a dynamic FMS index. By taking into account the order of finger movements in the motor sequence, the possible inversions of fingers during the task were automatically penalized. To report motion regularity, the dynamic FMS index was evaluated for each trial using the following equation:

$$Dynamic\ FMS\ index_{trial} = \left(1 - \frac{t_{max} - t_{min}}{t_{total}}\right) X\ 100$$

t_{max} : largest time interval between two final finger positions.
t_{min} : smallest time interval between final finger positions
t_{total} : total execution time

Finally, the dynamic FMS index was calculated as the average of the three indexes obtained from the three trials. Higher indexes reflected gestures performed with greater regularity.

2.4 Procedure

The entire protocol required two 30-minute sessions. The first individual session took place at home or school and was dedicated to the assessment of finger gnosia and early numerical abilities. The order of tasks was counterbalanced across participants. At the end of the first session, the experimenter presented the 3D device to the child and placed demonstration markers on their fingers to familiarize them with the materials.

The second 30-minute session was conducted in the motion laboratory of the local university to assess the precision of static and dynamic FMS. After a time of acclimation to the environment, markers were placed on the participant's preferred hand. The experimenter ensured that all children felt comfortable with the equipment before beginning the session. He stopped whenever the child expressed discomfort. Static and dynamic FMS tasks were administered in a counterbalanced random order, separated by a few minutes' break.

2.5 Analyses

Results were analysed in two stages using SPSS Statistics software (version 28.0; IBM Corp., 2020). The predictive value of sensorimotor finger skills on early numerical and arithmetical abilities was first examined using partial correlations followed by hierarchical multiple regressions. The chronological age was systematically considered as a covariate. Only the variables significantly correlated with early numerical abilities were selected for regression analyses. As biomecanical data from 3D motion analyses were less subject to observation and interpretation biases and provide more sensitive measure of gesture quality than behavioral measure (i.e., wider score distribution), only biomechanical data were considered for regression. Hierarchical multiple regression analyses were conducted to identify the significant predictors of early numerical abilities. In addition to regression analyses, bias-corrected bootstrap mediation analyses (Preacher & Hayes, 2008) were conducted to examine the pathways underpinning the relationships between sensorimotor skills and early numerical abilities. Analyses were carried out with 5,000 bootstrap samples and 95% confidence intervals (CI). To be included in the mediation analyses, variables investigated had to be reciprocally significant predictors. Effect size magnitudes were described throughout the results section based on Cohen's benchmarks (1988). Correlations (*r*) of .10, .30, and .50 were considered as small, moderate, and strong, respectively.

3 Results

3.1 Descriptive analyses.

Table 1 reports descriptive statistics for sensorimotor, numerical, and arithmetic skills, as well as the distribution of children as a function of their cardinal knowledge level and descriptive information about age, academic level, and possible limitations resulting from their verbal sequence knowledge. The enumeration and static FMS tasks showed high internal consistency (Cronbach alpha=.83 and .85, respectively) while this was low for the finger gnosia task (Cronbach alpha=.46). The proportion of small 'subset-knowers' (47%) was quite similar to that of large 'subset-knowers' (53%) for the age range considered here. Only 8/34 children reached the highest numerosity (within the limits of this experimental design) and could be considered as cardinal-principle-knowers. A large majority (91.2%) of the children were able to recite the verbal number sequence beyond the limit of their cardinal principle knowledge as assessed in the Give-N task, suggesting that they are not limited in their knowledge of the verbal routine to solve the cardinal task.

Table 1. Descriptive statistics of early mathematic and sensorimotor skills and the distribution of children as a function of their cardinal knowledge level.

	Mean score (SD)	Range Min.	Range Max.
Sensorimotor finger skills			
Finger gnosia	8.3 (1.4)	4	10
Static FMS task score	7.3 (2.4)	2	10
Static FMS index	0.3 (0.1)	0.2	0.5
Dynamic FMS task score	1.67 (1.1)	0	3
Dynamic FMS index	44.2 (34.1)	-20.2	94.6
Composite FMS index	0.0 (1)	-2.1	1.3
Early mathematical skills			
Verbal number sequence	11.5 (6.6)	0	20
Enumeration	5.5 (2.1)	0	8
Give-a-Number	5.1 (3.4)	2	10
Early arithmetic	3.1 (2.4)	0	9

Cardinal knowledge Level	n	Mean age [a] (SD)	Range Min	Range Max	Preschool level [b] 1	Preschool level [b] 2	Verbal number sequence > GaN [c]
Small SS-knowers	16	47.2 (7.2)	39	59	13	3	14 (87.5%)
One	0	-	-	-	-	-	-
Two	14	46.8 (6.4)	39	59	13	1	12 (85.7%)
Three	2	58.5 (0.7)	58	59		2	2 (100%)
Large SS-knowers	18	54.7 (7.1)	39	63	6	12	17 (94.4%)
Four	4	45.0 (4.9)	39	51	4		3 (75%)
Five	1	48.0			1		1 (100%)
Six	2	59.5 (2.1)	58	61		2	2 (100%)
Seven	0						
Eight	2	55.0 (8.5)	49	61	1	1	2 (100%)
Nine	1	61.0				1	1 (100%)
Max-knowers [a]	8	58.4 (3.5)	53	63		8	8 (100%)
Total	34	51.7 (7.7)	39	63	18	16	31 (91.2%)

Note. GaN= Give-a-Number. SS= subset. For each cardinal knowledge level, the table reports descriptive information about their age and their academic level. . [a] in month. [b] Level 1 and 2 correspond to the first and the second academic year in preschool. [c] Proportions of children whose knowledge of the verbal number sequence outperformed their cardinal knowledge level (based on known data, n = 29).

3.2 Correlations and hierarchical multiples regressions

Table 2 reports the Pearson's correlations between chronological age, early mathematical skills, and sensorimotor finger skills. Early mathematical skills and sensorimotor finger skills correlated significantly with chronological age. Partial correlation controlling for age indicated a moderate to strong significant correlation between static and dynamic FMS indexes and cardinal principle knowledge as well as between finger gnosia and arithmetic skills. However, no significant partial correlation was found between finger gnosia and cardinal principle knowledge, nor between sensorimotor finger skills and enumeration.

The correlations between static and dynamic FMS indexes and scores were strong, reflecting the convergent validity of biomechanical measurements from 3D motion analyses. No significant correlation was found between finger gnosia and the static and dynamic FMS scores and indexes. In contrast, the correlation between static and dynamic FMS indexes was strong (r=−.74) even after controlling for chronological age (r=−.57), suggesting that the two measures might not be independent. In preliminary analyses, some evidence of multi-collinearity emerged (i.e., tolerance and Variance Inflation Factor (VIF) scores of 0.3 and 2.6, respectively) likely attributable to this strong correlation, suggesting that these two variables may reflect different measures of the same construct. According to Allison (1999), the presence of multi-collinearity is confirmed when the VIF score is over 2.5 and the tolerance score is below 0.4. In this case, a cautious attitude has been favoured to ensure that the following models were free from multi-collinearity. Therefore, a composite FMS index (cFMS index) was extracted from static and dynamic FMS indexes by applying a principal component analysis (PCA). Results of the PCA confirmed that static and dynamic FMS indexes reflected a single construct, accounting for 87% of the total variance across FMS indexes. A similar amount of variance (.54) was extracted from each of the two indexes. Partial correlation controlling for age showed a significant association between the cFMS index and cardinal principle knowledge (r=.61, p<.001; strong association) and arithmetic skills (r=.48, p=.005; moderate association). In contrast, the cFMS index did not correlate significantly with finger gnosia (r=.17, p=.34) nor with enumeration skills (r=.27, p=.14).

Table 2: Pearson's correlations between chronological age, early numerical abilities and sensorimotor finger skills.

	1	2	3	4	5	6	7	8	9	10
Control										
1. Age	-									
Early mathematical skills										
2. Enumeration	.49**	-	.37*	.33	.17	.16	.28	-.22	.27	.27
3. Give-a-Number	.63***	.56***	-	.65***	.22	.41*	.59***	-.49**	.58***	.61***
4. Early arithmetic	.58***	.52**	.78***	-	.40*	.26	.38*	-.38*	.46**	.48**
Sensorimotor finger skills										
5. Finger gnosia	.56***	.38*	.48**	.59***	-	.18	.17	-.14	.17	.17
6. Static FMS score	.53***	.38*	.61***	.49**	.42*	-	.60***	-.65***	.64***	.73***
7. Dynamic FMS score	.36*	.41*	.66***	.50**	.31	.66***	-	-.53**	.79***	.75***
8. Static FMS index	-.63***	-.46**	-.69***	-.61***	-.44*	-.76***	-.61***	-	-.57***	-.88***
9. Dynamic FMS index	.60***	.48**	.74***	.65***	.44*	.76***	.81***	-.74***	-	.89***
10. Composite FMS index	.66***	.50**	.77***	.67***	.47**	.81***	.76***	-.93***	.93***	-

Note. Simple correlations are presented below the diagonal and partial correlation controlling for age are presented above. * $p \leq .05$;

**

Two hierarchical multiple regressions (Table 3) were conducted to examine the predictive value of sensorimotor finger skills on cardinal principle knowledge and arithmetic skills respectively, beyond the influence of age. Chronological age was entered in stage 1 while finger gnosia and the cFMS index were entered additionally in stage 2. Regarding cardinal principle knowledge development, the complete model explained 63% of the variance. Chronological age explained 40% of the total variance ($F(1,32)=21.50$, $p<.001$) while finger gnosia and cFMS index entered in the second stage explained an additional 23% of variance ($F(2,30)=9.09$, $p<.001$). Only the cFMS index came out as a significant individual predictor of cardinal principle knowledge ($p<.001$).

For arithmetic skills, the complete model explained 56% of the variance. Both finger gnosia ($p=.04$) and the cFMS index ($p=.01$) came out as significant predictors of early arithmetic skills. Chronological age explained 34% of the total variance ($F(1,32)=16.13$, $p<.001$) while finger gnosia and cFMS index accounted for an additional 22% of total variance ($F(2,30)=7.54$, $p=.002$). Interestingly, with the stepwise method in stage 2, finger gnosia no longer came out as a significant predictor ($p=.09$). The complete model explained 49% of the total variance. Chronological age explained 39% of variance ($F(1,32)=19.13$, $p<.001$) while cFMS index accounted for an additional 10% of the total variance ($F(2,31)=13.8$, $p<.001$).

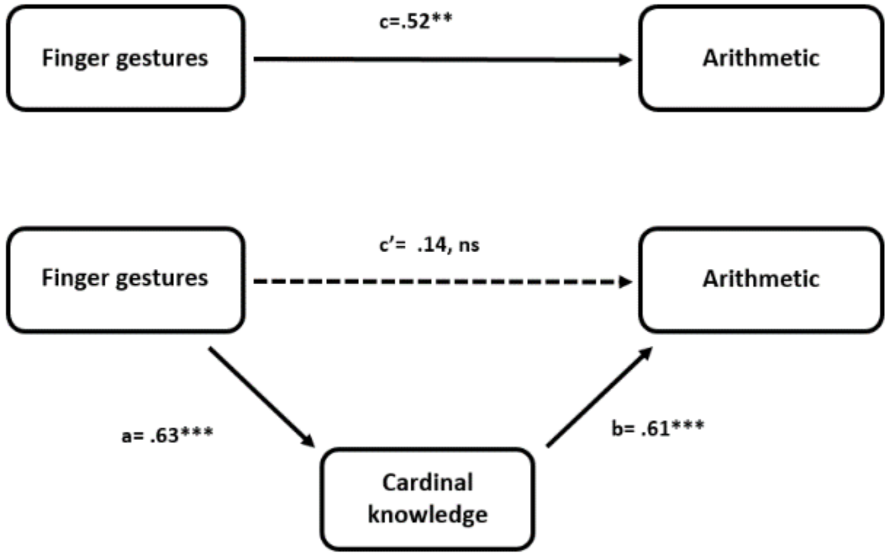
Table 3. Summary of hierarchical multiple regression analyses predicting cardinal meanings of NW and arithmetic fluency by sensorimotor skills, controlling chronological age.

Variables	**Cardinal knowledge**				**Arithmetic skills**			
	β	R^2	ΔR^2	Partial correlation	β	R^2	ΔR^2	Partial correlation
Stage 1		.40				.34		
Age	.63***				.58***			
Stage 2		.63	.23***			.56	.22**	
Age	.18			.20	.10			.10
Finger gnosia	.08			.12	.32*			.38
CFG index	.61***			.60	.46**			-.46

Note. CFG= composite finger gestures. * $p \leq .05$, ** $p \leq .01$, *** $p \leq .0$

3.3 Mediation analyses

With regard to the second issue, these relationships were further explored using mediation analysis, controlling for chronological age, to examine whether the influence of FMS on arithmetic could be mediated by cardinal principle knowledge development. From a functionalist point of view, the FMS targeted here might support cardinal principle knowledge (through cardinal finger gestures) which could then be a mediator in the relationship between FMS skills and arithmetic. As shown in Figure 3, the relationships between the cFMS index and cardinal principle knowledge (path [a], β=.63, $p \leq .001$), between cardinal principle knowledge and arithmetic (path [b], β=.61, p=.002) and between the cFMS index and arithmetic (path [c], β=.52, p=.01) were all significant prior to the addition of the mediator. Adding cardinal principle knowledge as a mediator of the relationship between the cFMS index and arithmetic made it no longer significant (path [c'], β=.14, p=.48). The bias-corrected bootstrap CI for indirect path (path [ab]) was entirely above zero (95%, [.41 to 1.79]) confirming that cardinal principle knowledge fully mediated the relationship between the cFMS index and arithmetic, after controlling for chronological age.



Note. $* p \leq .05$, $** p \leq .01$, $***p \leq .001$.

Figure 3: Path coefficients of the mediation model where cardinal knowledge mediates the relationship between CFG index and arithmetic skills.

4 Discussion

The aim of the present study was to investigate the relationship between sensorimotor finger skills and early mathematical abilities in typically developing young children. To this end, we explored the predictive value of finger gnosia, static and dynamic FMS in enumeration, cardinal principle knowledge, and early arithmetic. Although static and dynamic FMS had to be merged into a single composite index, results showed that both FMS and finger gnosia significantly predicted performance in a simple addition task with pictorial support, but FMS turned out to be a better predictor of early arithmetic skills in this task than finger gnosia. Moreover, FMS were a unique predictor of cardinal principle knowledge, and neither FMS nor finger gnosia were significant predictors of enumeration skills. Finally, mediation analyses showed that cardinal principle knowledge fully mediates the relationship between FMS and arithmetic.

The first objective of this study was to examine the specific contribution of FMS involved in finger-based numerical representations to early numerical and arithmetic skills. Accordingly, specific predictions were made about the possible relationship between static or dynamic FMS and enumeration, cardinal, or arithmetic tasks. Yet, static and dynamic FMS assessed in the current study could not be distinguished in the analyses due to the multi-collinearity between the two predictors. This lack of independence suggests that they refer to very similar motor processes and that the variance related to each variable could not be reliably discriminated. Thus, the present study provided no evidence that static and dynamic FMS tasks measure different constructs in their current state.

A second objective was to assess the predictive relationship between sensorimotor finger skills and arithmetic. Both finger gnosia and cFMS index came out as significant predictors, a result in agreement with previous evidence supporting the relationship between arithmetic skills and finger gnosia (Fischer et al., 2022; Newman, 2016; Noël, 2005; Reeve & Humberstone, 2011; Wasner et al., 2016) or FMS (Asakawa et al., 2019; Gracia-Bafalluy & Noël, 2008) in school-aged children (for a review, see Neveu et al., 2023). However, FMS were found to be the best predictor of early additive skills, and finger gnosia did not account for any additional variance after FMS had been selected in the model. One possible explanation would be to consider that finger gnosia is a pre-requisite to fine finger movements related to finger-based arithmetic solving strategies (i.e., finger-counting and cardinal finger gestures). To be able to move fingers in coordinate sequence (i.e., dynamic FMS, as requested in finger-counting) or to put one's fingers in a particular configuration (i.e., static FMS, as involved in cardinal finger gestures), the child should have a clear and integrated representation of the fingers on their own hand, that is, good finger gnosia. Finger gnosia would no longer be a significant predictor once FMS were taken into account in the stepwise regression model because FMS would have captured a larger part of the shared variance. However, this interpretation seems unlikely as no significant correlation was found between finger gnosia and FMS indexes when age was controlled for. As another explanation, the task used to assess finger gnosia presents limited reliability, suggesting internal consistency problems between items. This might explain the lack of sensitivity of this measure, a problem that has already been reported in other studies that reported a comparable Cronbach alpha (e.g., Cronbach alpha=.55 in Wasner et al., 2016; see Wasner et al., 2016, and Barrocas et al., 2020, for a discussion). Although this is a classic measure, future investigation should examine a more reliable measure of finger gnosia.

A third objective was to examine the predictive relationship between sensorimotor finger skills and verbal cardinal knowledge development. Overall, the composite FMS index came out as a unique and strong predictor of cardinal principle knowledge in young children. By contrast, neither finger gnosia nor FMS predicted enumeration abilities, which put no or less emphasis on complex finger movement. In the debate between authors who claim that fingers support the development of cardinal principle knowledge (Gibson et al., 2019; Gunderson et al., 2015) and those who argue that cardinal finger gestures provide no advantage in the acquisition of cardinal concepts (Nicoladis et al., 2010), these results add to existing evidence highlighting the *specific* contribution of FMS to cardinal principle knowledge. Recently, it has been shown that training verbal cardinal principle knowledge would be more effective when enriched with cardinal finger patterns (Orrantia et al., 2022). In line with these findings, the current results suggest that fingers would be a gateway to access the cardinal meaning of verbal number words (Di Luca & Pesenti, 2008; Krinzinger, 2011). When congruent with counting habits, fingers provide an iconic representation of numerosity that could be recognized as a whole, halfway between symbolic and non-symbolic representations of number magnitude, bridging the gap between them (Andres et al., 2008; Di Luca & Pesenti, 2008, 2011; Gunderson et al., 2015; Krinzinger, 2011). Their dual symbolic and non-symbolic status would support the threefold relationship between cardinal finger gestures, the numerosity conveyed by fingers, and the concomitant uttered number-word (Gibson et al., 2019; Gunderson et al., 2015). Altogether, this evidence strengthens the functionalist hypothesis, which assumes that

FMS could support the development of ordinal and cardinal numerical representation, presumably through their contribution to finger-based numerical representations.

Interestingly, mediation analyses conducted here indicate that cardinal principle knowledge mediates the relationship between FMS and arithmetic skills, suggesting that FMS indirectly contribute to early arithmetic skills through cardinal principle knowledge. This finding provides new insights into the functional mechanisms by which FMS promote arithmetic development in young children. In previous work, Pitchford et al. (2016) showed that FMS were related to arithmetic performance in five to six-year-olds in the first year of primary school, but not in four to five-year-olds in the foundation year, suggesting that FMS would only support children's numerical development once they were able to use finger-based solving strategies to calculate. The present results not only suggest that such a relationship exists in young children as young as three to five but also that it is mediated by the contribution of fingers to the acquisition of the cardinal concepts. Thus, FMS would give the child access to understanding the meaning of number words, which lay the foundation for arithmetic skills. The present results are consistent with models depicting how finger-use promotes the formation of cardinal concepts, themselves being a preliminary step to early arithmetic skills (Krajewski & Schneider, 2009; Roesch & Moeller, 2015).

Future investigations should confirm these results by enlarging the sample size, which was limited here, and should be conducted with finger gnosia and FMS tasks of equivalent sensitivity to better understand the triadic relationship between finger gnosia, FMS, and early numerical and arithmetic skills. Furthermore, while thinking about more reliable measures of finger gnosia, it would be interesting to shed light on the nature of the perceptual processes involved in finger gnosia that are useful to numerical processing development. Finger gnosia are assessed through tactile input on the finger skin, yet their contribution to numerical processing could be more proprioceptive than tactile in nature. As a cognitive pre-requisite of finger gestures (Hay et al., 2005), finger proprioceptive representation might provide a more intuitive account of how perceptual components contribute to numerical processing. In future work, specific attention should be paid to the distinction between tactile and proprioceptive representation in order to clarify which of these two perceptual components predicts children's arithmetic development. Moreover, given the relationship between FMS and early numerical skills, implementing FMS training would be useful to examine the causal relationship between FMS and early numerical skill development in preschool-aged children. Previous investigations have found an improvement of arithmetic skills after FMS training in primary school children (Asakawa et al., 2019; Gracia-Bafalluy & Noël, 2008). Similarly, a randomized controlled trial could be conducted to test whether FMS training could improve preschoolers' cardinal principle knowledge and transfer, through cascading effects, to more mature numerical abilities such as early arithmetic skills.

To sum up, this research is the first to use a 3D motion analyses to provide new evidence for the contribution of FMS to numerical and arithmetic skills in young children. Using an innovative fine-motion recording technique, the present work provided fine-grained biomechanical data on finger movements. For future investigations, this 3D motion analyses could be fine-tuned to assess the quality of fine finger gestures in several situations as a function of the task goal (i.e., finger placement on pegboard rods, finger lift amplitude in tapping tasks, etc.). The recording system could also be synchronized with a voice recording device to assess the synchronization of finger movements and verbal production such as finger counting, for instance. Unlike behavioral measures which are often limited to dichotomous measures (i.e., correct or incorrect execution of the gesture), 3D motion analyses provide the advantage of reporting the performance on a continuum so as to account for the entire spectrum of possible performances, thus improving the sensitivity of the measures. On the other hand, as the measurement tool is a stationary system, measurements can only be done within a laboratory, which makes the tool unsuitable for large-scale field assessments. In this study, these first findings are promising and open new avenues for future work.

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Partie 3 : Phase expérimentale conduite auprès d'enfants avec des troubles moteurs

Chapter 6 - Finger counting to relieve working memory in children with developmental coordination disorder: Insights from behavioral and 3D motion analyses.

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Abstract

Very few studies have attempted to understand how motor deficits affect numerical abilities in children with developmental coordination disorders (DCD). The purpose of this study was to explore the functionality of finger counting (FC) in children with DCD. Twelve children with DCD and 12 typically developing children matched on school-level and fluid reasoning abilities were asked to use FC to solve an ordinal task with high working memory load. Behavioral measures supplemented by biomechanical measures from 3D motion analyses synchronized to a voice recording were used to assess children's performance and FC functionality (total duration, inter-finger transition, regularity, finger/voice synchronization, and automatization of FC movements). Children with DCD were less accurate than typically developing children in using FC to solve ordinal problems with high working memory load. This group difference could not be accounted by poor FC skills as FC movement turned out to be as functional in children with DCD as in their TD peers. When added to the model, working memory captures the majority of the variability explaining this group difference, providing evidence that their difficulties would instead be rooted in limited working memory resources.

Keywords: developmental coordination disorder, finger counting, working memory, 3D motion analyses, finger-counting functionality.

1 Introduction

In many cultures around the word, children use their fingers to deal with numbers (Bender & Beller, 2012; Fuson, 1988). From the age of three, they begin to use finger-counting (FC) in a variety of numerical contexts. Each finger is then raised individually, in one-to-one correspondence with a number-word, ending with a number-gesture that provides a cardinal representation of the last number-word stated. A growing body of evidence suggests that intrinsic properties of the FC play a key role in the development of children's mathematical skills (Alibali & DiRusso, 1999; Gelman & Gallistel, 1978; Gibson et al., 2019; Graham, 1999; Thevenot et al., 2014). In their developmental model, Roesch and Moeller (2015) explained how these properties contribute to the development of early numerical and arithmetic skills. By associating each raised finger with a specific number-word, the FC support the segmentation of the verbal number sequence and emphasizes the order in which number-words should be recited (Beller & Bender, 2011; Crollen, Seron, et al., 2011; Roesch & Moeller, 2015). Furthermore, number-gesture produced during FC provide an iconic representation of the represented quantity supporting the understanding of cardinality of verbal symbols (Di Luca & Pesenti, 2008; Gunderson et al., 2015; Krinzinger, 2011; Wasner et al., 2015).

Building on the development of early numerical skills, FC forms the basis on which young children rely to acquire their first arithmetic abilities (Bartelet et al., 2014; Major et al., 2017). Since fingers are used as an external support to visualize and combine the quantities involved in computations (Baroody, 1987; Björklund et al., 2019; Kullberg & Björklund, 2020), they are often described as an ideal tool for relieving the load on working memory (WM) inherent to this type of task (de Chambrier et al., 2018; Passolunghi & Cornoldi, 2008). As such, when solving numerical problems with high WM load (e.g., solving additive problems with carry such as 23+18 or performing advanced counting such as enumerating the number of items between two elements in an ordered sequence), children use FC to keep track of the counted items thus relieving their WM (Crollen, Mahe, et al., 2011; Kullberg & Björklund, 2020). Mainly used in young children with low WM resources, FC gradually decreased during the elementary school years as children have sufficient cognitive resources to switch from FC to more powerful mental calculation strategies (Geary & Brown, 1991; Jordan et al., 2008; Poletti et al., 2022). This transition was found to occur later in children with mathematical learning disabilities (MLD) who have limited WM resources (De Smedt et al., 2013; Mazzocco et al., 2011). These children were shown to make more extensive use of concrete supports such as fingers, which provides them with a physical representation of number while reducing the WM load in the task (Noël, 2005, 2009; Passolunghi & Cornoldi, 2008). Therefore, children with MLD keep on using FC longer between grade 1 to 3 and use fewer mental strategies (i.e., arithmetic facts retrieval, decomposition of numbers) compared to their typically developing peers (Geary & Brown, 1991, Jordan et al. 2003, Wylie et al. 2012).

Naturally, FC rely on fine motor skills. For the FC to be functional, children must be able to raise their fingers in one-to-one correspondence with number words in a coordinated and regular movement. FC movement must also be sufficiently automatized so as not to add an additional cognitive load in working memory (WM). Interestingly, some children with MLD were found to exhibit fine motor skills impairment similar to those observed in children with developmental coordination disorders (DCD) which might impede their FC movement (Pieters et al., 2015). Surprisingly, in children with DCD who are known to suffer from severe and persistent motor impairment (Wilson et al., 2012), the functionality of the FC has never been examined so far. Yet, in addition to their motor disorder, these children were also found to have poor WM resources (Alloway & Archibald, 2009; Rigoli et al., 2013). They would therefore be doubly penalized in performing arithmetic operations with, on one hand, limited resources in WM and, on the other hand, restricted possibilities for using FC strategies to relieve their WM.

Little is known about the characteristics of mathematical difficulties in children with DCD. An initial series of investigation provided evidence of poor number sense in children aged of seven to ten years (Gomez et al., 2015, 2016). Moreover, their counting skills were found to be limited, an impairment which would be due to oculomotor dysfunctions reducing their ability to track targets by pointing (Gomez & Huron, 2020). Difficulties in executing calculation solving procedures has also been reported in nine years old children with DCD, particularly when associated with severe motor impairments (Pieters, Desoete, Waelvelde, et al., 2012). Some authors suggested that their difficulty might results from poor knowledge of the numerical system or a lack of automatization of calculation procedures (Pieters, Desoete, Waelvelde, et al., 2012), but another source of impairment could be their difficulty in deploying functional FC movements in relevant mathematical tasks.

Thus, the main aim of this study was to investigate the functionality of FC in children with DCD. First, we examined whether children with DCD could use FC efficiently to solve a task with high WM load (named the N^{th}-After task). Children with DCD were asked to use FC to determine what is the n^{th} element after a target in an ordered sequence. As children with DCD present a higher risk of arithmetic learning difficulty (Pieters, Desoete, Roeyers, et al., 2012), FC was implemented in a simple ordinal task with high WM load to avoid potential confound with arithmetic disability. Moreover, the task had to be performed with numerical *vs* non-numerical ordered sequences to examine the influence of the type of sequence on performance. If fine motor impairments reduce children's ability to use efficient FC strategies to relieve WM, children with DCD should be less accurate than their typically developing peers in the ordinal task whatever the condition (letters or numbers).

Finger-counting functionality was further explored using 3D motion analyses combined with voice recording. Four different biomechanical parameters were assessed to examine FC functionality namely, total duration, inter-finger transition (as a measure of speed of execution), regularity and finally, finger/voice synchronization. Contrasting with the N^{th}-After task, FC was further examined in two control FC tasks with lower WM demands to determine whether FC functionality in each group was influenced by the WM requirements of the task. The two control tasks respectively involved low- (i.e. finger counting up to ten), and no-demand (i.e. execution of finger-like counting movement with no recitation) in WM. If FC is cognitively demanding in children with DCD, increasing the task WM load should deteriorate FC functionality (as assessed through the four biomechanical parameters) in the DCD group in comparison to typically developing children. In this case, FC is expected to be less functional in the N^{th}-After task than in the two other tasks in children with DCD compared to their typically developing peers. Conversely, if FC is automatized and effortless in children with DCD, FC functionality should be similar whatever the task WM load.

2 Method

2.1 Participants

Twenty-four French speaking children participated in the experiment: 12 children with DCD (Mean age = 8.8 ± 0.56 years) and 12 control typically developing children (Mean age = 8.7 ± 0.75 years). All children were enrolled in mainstream elementary school.

Children were recruited between September 2020 and July 2022 through newsletters distributed by teachers in local schools and by therapists practicing in multidisciplinary centers. Short letters were also published through social networks. Initially, 56 parents answered the call (18 of children with DCD, 38 of typically developing children). After contacting them, children were encountered a first time to ensure that they met the inclusion criteria of the study. All children were asked to complete the four manual dexterity subtests of the MABC-2 (Henderson et al., 2007. i.e., placing pegs, threading lace, drawing trail) and the four verbal comprehension and fluid reasoning subtests of the WISC-V (Wechsler, 2016.; i.e., Similarity, vocabulary, matrix reasoning, figures weights). Parents of all participants were invited to complete an anamnestic questionnaire about their child. Only parents of a child with DCD completed the MABC-2 motor questionnaire.

The present study used strict inclusion criteria to ensure that all children included in the DCD group actually had a clear clinical diagnosis of DCD. As such, all children in the DCD group have been diagnosed by a physician on the basis of the DSM-5 diagnostic criteria (American Psychiatric Association, 2013). In addition, to confirm the diagnosis, each criterion of the DSM-5 was assessed through objective measurement. To be included in the DCD group, children had to exhibit poor fine motor skills with a manual dexterity index of the MABC-2 below the 10th percentile (DSM-5 criterion A). The scores of the MABC-2 motor questionnaire completed by their parents had to be below of the 5th percentile, indicating that their motor impairment interfered with daily activities (DSM-5 criterion B). Moreover, their motor disorder could not to be explained by others medical conditions (e.g., epilepsy, hydrocephalus, cerebral palsy; DSM-5 criterion C), which was confirmed by the anamnestic questionnaire filled out by parents. Finally, children had to have the WISC-V verbal comprehension and fluid reasoning indexes above 80 (DSM-5 criterion D). Each child in the DCD group was matched with a typically developing child on the basis of their school-level and their fluid reasoning abilities as assessed with the figure weights subtest of the WISC-V which present limited visuo-spatial processing requirement (Van Dyck et al., 2022; max 2 points difference in standard score within the matching pair). To be included in the control group, children had to score above the 25th percentile on the MABC-2 manual dexterity index and parents should report no history of motor difficulties in the anamnestic questionnaire.

Among the 18 children with DCD who answered the call, four did not fulfill one of the four criteria of the DSM-5 based on the objective measurements and were excluded from the sample: three of them had a manual dexterity score above the 10th percentile (from P16 to P25), and the last child was excluded as parents reported hydrocephalus at birth. The parents of two children withdrew from the study because they were unable to attend the second test session. Twelve children were selected to be matched to each of the subjects with DCD by choosing those who presented the best fit in terms of school level and figure weights subtest score.

The anamnestic data collected through questionnaires revealed that ten on the 12 children included in the DCD group had comorbidities (i.e., learning disabilities and/or attention deficit disorder) and nine were followed by a speech or an occupational therapist at the time the study was conducted. The socio-economic status of the families, collected with the International Standard Classification of Occupation (ISCO-08; International Labour Organization [ILO], 2008), was heterogeneous, with

45.8% of parents working as managers or in an intellectual profession, 29.2% as factory workers and 12.5% as administrative employee or technician. 8.3% of parents reported not having occupation and the socio-economic status of 4.2% was unknown.

This study was not preregistered. The research was approved by the local ethic committee (reference number: 1920-116). The parents of participants as well as children gave written informed consent. Each child has been informed orally of the research and consented it.

2.2 Tasks

The experimental protocol included three FC tasks with different WM-demands. A 3D motion measurement equipment was used to collect biomechanical data in the three FC tasks. Working memory and knowledge of ordered numerical and non-numerical sequences were also assessed in two additional control tasks.

N^{th}-After task. Adapted from Crollen et al. (2011), the N^{th}-After task was administrated to assess the ability to use FC to solve problems involving ordered numerical and non-numerical sequences. Specifically, the child was asked to identify the n^{th} item after a target item using two types of ordered sequences. The task involved the verbal number sequence in the numerical condition (i.e., "What is the n^{th} number after *x*?") and the alphabetical sequence in the non-numerical condition (i.e., "What is the n^{th} letter after *x*?"). The child was explicitly asked to count on his finger from the term $x+1$ and to continue until *n* fingers were raised according to the following instruction: "Now I'm going to ask you what is the n^{th} number/letter after *x*? To answer this question, you will put *x* in your head and continue to count/recite the alphabet from $x+1$ by raising one finger for each number/letter. You will stop when you have raised *n* fingers". The experimenter made a first demonstration and then invited the child do it in turn. Thus, the task has been designed to place a high load on WM (i.e., memorizing the starting point, the number of steps and then reciting the sequence until the target was reached), making FC a relevant strategy for relieving WM. The child was asked to state his/her answer aloud. In each condition, the task consisted of two sets of eight ordinal problems requiring the child to raise two to nine fingers (i.e., 16

items by condition). Half of the items involved two to five fingers and can be done with one hand while the other half involved six to nine fingers and required the use of both hands. Three training trials involving respectively, the raising of one, two and three fingers were administrated before starting the task to ensure that the instructions were properly understood. One point was given for each correct answer.

Finger-counting. To assess FC, the child was asked to count from 1 to 10 on his fingers, starting with is dominant hand. This task only required coordinating finger movements with the recitation of the verbal number sequence and thus, place lower load on WM. The participant had to complete the FC sequence three times to obtain a stable measure of his performance.

Counting-like finger movement. This task was designed to assess counting-like finger movement with no recitation and thus involved no cognitive load in WM. The child had to execute an ordered sequence of finger movements simulating FC (i.e., starting with the hand closed and raising finger one by one following the order of their anatomical position: thumb, index, middle, ring and pinky finger), starting with his dominant hand. The participant was asked to complete the sequence of counting-like finger movement three times to obtain a stable measure of his performance.

Ordered sequences. This task assessed the child's knowledge and level of development of ordered sequences which were considered as pre-requisite for the N^{th}-After task. First, the child was asked to recite the numerical sequence (from 1 to 30) and the alphabetical sequence (from a to z). Second, he/she had perform *advanced recitation*, that is, reciting the ordered sequences between two target points (e.g., for the numerical sequence "*Can you count between 5 and 13*?", for the alphabetical sequence "*Can you recite the alphabet between e and m*?"). This ensure that the child reached the breakable chain level of knowledge for each sequence (Fuson, 1988), an ability which is fundamental to perform the N^{th}-after task. Five trials were administered for each type of sequence, one for the sequence recitation and four for advanced recitation between two targets, for a total of ten trials. One point was awarded for each correct answer. To be included in the present study, the child had to provide at least eight correct answers.

Working memory. Working memory abilities were assessed using a backward letter span task. The stimuli consisted of a set of 21 sequences of letters of increasing length (i.e., two to nine letters). The participant had to repeat, in the reverse order, a letter sequence read aloud by the experimenter. The task began with two trials of two-letters sequences. Participant had to succeed two trials of the same length to be presented with span+1, with a maximum of three trials per span. Two training trials of two-letters length were administrated before starting the task. Each correct answer was credited with one point.

2.3 3D motion acquisitions and processing

Data acquisition. Four units of Codamotion 3D optoelectronic system (Charnwood Dynamics Ltd, UK) were used to localize, with millimeter precision (Schwartz et al., 2015), the eight 3D markers placed on each participant's hand (i.e. one on the distal phalange of each finger, one on the proximal phalange of index, one on the middle finger metacarpal and one on the distal wrist crease). Acquisitions were performed at a frequency of 200 Hz. Voice recording was made by a microphone placed on the child's clothing, close to the mouth and was synchronized with the 3D motion acquisitions.

Data processing. Data processing was performed on Matlab R2017a software. As illustrated in Figure 1, processing consisted of (1) targeting, from 3D motion analyses, the time the child started to lift each finger, (2) targeting, from acoustic recording, the time the child started the recite each term of the ordered sequence, and (3) mapping the signals to each other.

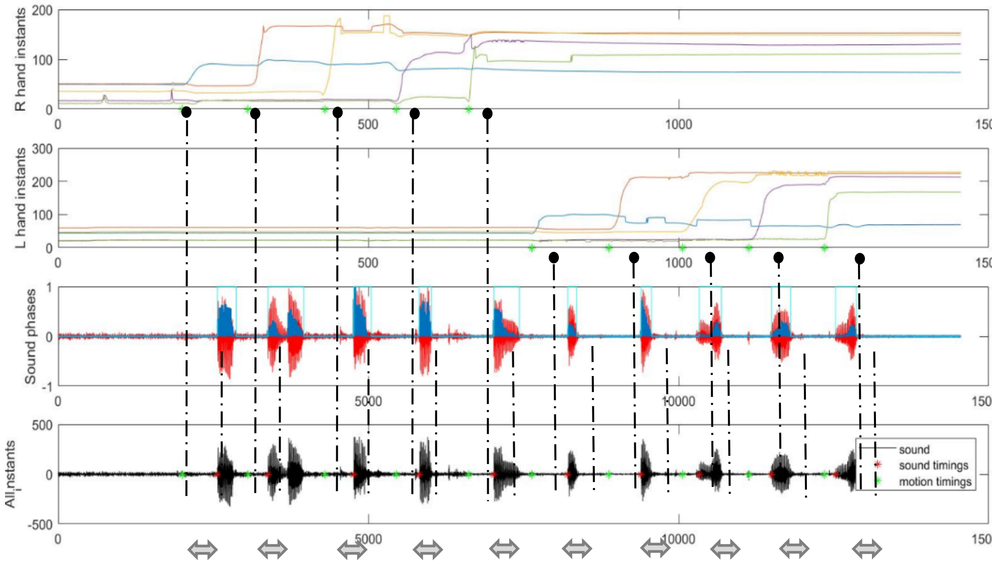

Figure 1: Example of data processing where acoustics and motor signals have been mapped. The grey arrows represent the time intervals between the moments when the participant started to lift his fingers and the moment when he/she started to speak.

Four different indexes were extracted from biomechanical data to assess movement functionality in each of the tasks involving finger movements (i.e., N^{th}-After task, finger-counting and counting-like finger movement), namely *total duration, inter-finger transition, regularity,* and *finger/voice synchronization indexes*. Because the calculation of the synchronization index requires both acoustic and motor signals, no synchronization index was extracted for the counting-like finger movement task, which involved no recitation.

First, a *total duration index* was calculated to measure the overall speed of execution of finger movements. For each item, the total duration index was calculated as the time interval between the beginning of the motor signal of the first finger raised and the beginning of the motor signal of the last finger raised. Second, an *inter-finger transition index* was considered as the average of the time intervals between consecutive finger raises (i.e., time interval between the beginning of the motor signal of each finger and the beginning of the motor signal of the next finger). Third, a *regularity index* was extracted to measure the regularity with which participant raised their fingers. For each item, the regularity index was calculated as the standard deviation of the time intervals between consecutive raised fingers. A larger index reflects a poor regularity in child's movement. Fourth, a *finger/voice synchronization index* was computed to assess the child's ability to synchronize fingers raising with the recitation of the ordered sequence. For each item, an index was computed as the average of the time intervals (in milliseconds) between the instant at which the child began to raise each finger and the instant at which he/she began to enunciate each term in the ordered sequence. To facilitate the interpretation of the data, the synchronization index for each item was transformed using the function $f(x)=-1$. Positive values reflect to voice occurring before raising fingers. A smaller index reflects better synchronization, with an index of 0 indicating a perfect match between finger lifting and number word/letter recitation.

2.4 Procedure

The entire protocol required two one-hour sessions. The first individual session took place at the child's home, and was dedicated to IQ, working memory and fine motor skills assessment to confirm that the participant met the inclusion criteria of the current research. At the end of the first session, the experimenter presented the 3D device to the child and placed demonstration markers on his/her fingers, to make him/her familiar with the material.

The second session was conducted in the Motion Laboratory of the local university to assess the child's ability to use FC. After a time of familiarization with the environment, the child was invited to sit on a chair placed in front of a school table, in the center of the four units of 3D system. Markers were then placed on his/her both hands. A blank trial was conducted before starting the session to ensure that the markers did not interfere with the participant's finger movements and that the child felt comfortable with the equipment. He was asked to inform the experimenters if he/she felt uncomfortable and when necessary, the markers were repositioned. None of the child reported persistent discomfort. The two conditions of the N^{th}-After task were administered in a counterbalanced order. The participant was offered a few minutes break between the two tasks. This second session was also recorded with a 2D camera.

2.5 Analyses

As the experimental phase resulted in some missing data mainly due to a lack of visibility of the 3D markers in some situations and since these models are recommended for dealing with small sample size (Meteyard & Davies, 2020), Generalized Linear Mixed Model (GLMM) were chosen to retain all available data in the analyses. The models were conducted using the general linear mixed-effects models procedure of the JASP 0.17 computer software. All items were individually encoded. The final models were selected based on the lowest BIC scores, reflecting a good fit with data. Binomial GLMM were used for analyses behavioral data (i.e., performance on the recitation and the N^{th}-After tasks) while Gamma GLMM were used for the biomechanical data (i.e., measures obtained from the four functionality indexes).

3 Results

3.1 Descriptive information

Table 1 shows descriptive information in DCD and control groups, mean performance in IQ, manual dexterity and working memory and t-test performed for group comparisons. The number of girls and boys in both groups was strictly identical (n=6). Both groups had equivalent socioeconomic status (χ^2=14.20, *p*=.16). Children in the DCD group were enrolled in the same grades as control children. Although two children with DCD repeated a grade, the two groups were balanced in terms of age (*t*(22)=.43, *p*=.67).

As expected, t-tests confirmed that children in the DCD group were significantly weaker than typically developing children in all three manual dexterity subtests of the MABC-2 (Placing pegs: *p*=. 003; Threading a shoelace: *p*<.001; Drawing a trail: *p*<.001) and in the mean score (*p*<.001). Regarding the WISC-V fluid reasoning index, no group difference was found in the figure weights subtest (*p*=.72), confirming that both groups have similar reasoning abilities. Unsurprisingly, the group difference in the matrix reasoning subtest was at the limit of the significance (*p*=.05), probably because of the task visuospatial processing requirement. However, no group difference was found in the fluid reasoning mean standard score (*p*=.20). With respect to the verbal comprehension index, groups comparisons showed that the similarity subtest scores (*p*=.004) were significantly lower in children with DCD compared to their peers. No significant difference was found on the vocabulary subtest (*p*=.06). Overall, the mean score of the verbal comprehension scale was significantly lower in children with DCD than in the control group (*p*=.01). All participants were able to recite ordered numerical and alphabetical sequences and reached the breakable level of knowledge for each sequence, scoring a minimum of 8/10 on the ordered sequences task.

Table 1. Descriptive information regarding IQ scores, fine motor skills and working memory in the DCD and control groups.

	DCD group (n=12)		Control group (n=12)		Groups comparisons
	Mean (SD)	Range min - max	Mean (SD)	Range min - max	$t(22)$
Age (in months)	105.50 (6.75)	92 – 119	104.08 (9.04)	91 – 119	.43
Gender (M/F)	6/6		6/6		
School level (G2/G3/G4)	3/6/3		3/6/3		
IQ (WISC-V)					
Mean fluid reasoning [a]	9.37 (2.34)	3.3 – 13	10.62 (2.34)	6.5 – 13	-1.31
Matrix reasoning [a]	8.50 (2.68)	5 – 13	10.58 (2.15)	7 – 13	-2.11
Figure Weights [a]	10.25 (2.34)	5 – 14	10.67 (3.20)	5 – 14	-.36
Mean verbal comprehension [a]	9.87 (2.16)	6.5 – 13	12.47 (1.96)	10 – 16	-3.01**
Similarity [a]	10.00 (2.29)	6 – 13	13.08 (2.39)	8 – 17	-3.22**
Vocabulary [a]	9.75 (2.56)	5– 14	11.75 (2.42)	7 – 16	-1.97
Manual dexterity (MABC-II)					
Placing pegs [a]	6.67 (2.50)	1 – 12	10.25 (1.77)	7 – 15	-3.33**
Threading lace [a]	6.33 (2.50)	3 – 11	10.50 (2.07)	8 – 13	-4.45***
Drawing trail [a]	3.75 (2.28)	1 – 12	9.58 (2.84)	4 – 12	-4.65***
Mean manual dexterity [a]	5.58 (1.54)	3 – 8	10.11 (1.21)	9 – 13	-8.01***
Working Memory					
Backward letter span	3.25 (1.21)	2 – 6	5.50 (1.13)	4 – 8	-4.35***

Note. G = grade; M = male; F = female. [a] standard note: Mean=10, SD=3. * $p \leq .05$; ** $p \leq .01$; *** $p \leq .001$.

3.2 Behavioral data

Behavioral data were analyzed in order to examine whether children with DCD were able to use FC when solving an ordinal task with high WM load (i.e., N^{th}-After task). A first GLMM model was conducted to compare accuracy between groups (DCD vs control) across the two experimental conditions (numerical *vs* alphabetical sequence) of the N^{th}-After task. Therefore, group, condition and group-by-condition interaction were added in the model respectively as first, second- and cross-level predictors. Participants and items were treated as random effect.

The results revealed that the group (SE=.33, $t(719)=-3.79$, $p<.001$) was a significant predictor of performance, reflecting that children with DCD had lower performance than the control group in the N^{th}-After task. The condition effect suggest a slight advantage of the numerical on the alphabetical condition but this effect failed to reach significance (SE=.17, $t(719)=-1.80$, $p=.07$). The group-by-condition interaction was not significant (SE=.16, $t(719)=.82$, $p=.41$). To determine whether the group effect could be explained by WM, performance in the backward letter span task was taken into account. When the WM was added to the model, most of the variability is captured by this covariate making the group effect non-significant (SE=1.26, $t(719)=1.27$, $p=.20$).

Moreover, errors made by participants during the N^{th}-After task were analyzed using 2D video recording. Seven categories of errors could be distinguished among the 181 errors identified[5]. Examples of each type of error to the question *What is the 7^{th} number after 4?* are provided between brackets.

A first category was referred as [*Finger word coordination errors*][6] which were related to the execution of the FC movements (i.e., observable lack of synchronization between finger lifts and enunciation). A second category of errors included *stop errors* due to an incorrect number of fingers raised during FC (i.e., raised fewer or more

[5] Note that error could cumulate the characteristics of two different categories and were thus counted twice.

[6] Note that changes made to the submitted manuscript are marked with square brackets in the thesis text.

fingers than required). The third type referred to *initiation error*, when the participant initiated the FC with a term other than *x* or *x*+1 (i.e., the child starts to count from [three] instead of five). Since all children demonstrated their ability to recite the numerical and alphabetical sequences between two targets before starting the task, the initiation errors could not be interpreted as an inability to initiate the recitation from an arbitrary entry point. Rather, *Stop and initiation errors* could be interpreted as reflecting WM errors related to difficulties in maintaining the instruction in WM during the processing of the N^{th}-After task. As a result, children started their counting from a wrong starting point or raised an incorrect number of fingers, (sometimes even stopping their counting only after having raised all their fingers).

Fourth, *instruction errors* were related to the execution of the instruction. An error was classified in this category when the child initiated his/her counting from the term *x* instead of the term *x*+1, despite the explicit instruction given before starting the task (e.g., the child initiated the counting from four instead of five). The fifth category encompassed *enunciation errors* which were related to an incorrect enunciation of the verbal numerical or alphabetical sequences (i.e., mainly errors caused by omissions of a term from the ordered sequence). A sixth type of error consisted of *reversal error* when the child reversed the number from which to start (i.e., term *x*) and the number of fingers to be raised (i.e., term *n*) (e.g., the child starts to count from eight and raises four fingers instead of staring from five and raising seven fingers). Finally, the last category concerns *unclassified errors* related to a lack of response or to errors that could not be classified in any category. *Instructional, enunciation, and reversal errors* were grouped, with the *unclassified errors*, under the heading of "Others errors." As these errors occurred occasionally, they can be interpreted as manifestations of inattention. They reflected neither a lack of understanding of the instructions, nor a poor mastery of the ordered sequences, since before starting the N^{th}-After task, all participants were able to perform the three training trials and to recite the ordered sequences.

Table 2. Distribution of errors in each groups in the Nth-After task.

Categories of errors	DCD group	Control group	Total [a]	Error Description
[Finger word coordination errors]	11	0	11	Lack of synchronization between fingers and verbal enunciation.
WM errors				
Stop	75	19	94	Number of fingers raised other than *n*.
Initiation	30	8	38	Initiation of FC with a term other than *x* or *x*+1.
Total	105	27	132	
Other errors				
Instruction	2	1	3	Initiation of FC from the term *x* instead of *x*+1.
Enunciation	5	2	7	Omissions of a term in the verbal sequence.
Reversal	21	2	23	Permutation of the terms *x* and *n*.
Unclassified	3	2	5	Lack of response and errors not classified.
Total	31	7	38	

Note. WM, working memory. Errors were described in response to the question: "What is the n^{th} number/letter after *x*?"

[a] Total refers to all errors made by participants of each group.

Table 2 summarizes the distribution of errors in each group in the N^{th}-After task. Taking a closer look at WM and [finger word coordination errors], children in both groups made more WM errors than [finger word coordination errors], but the distribution of these two types of errors did not differ between groups (χ^2=2.77, *p*=.10). Children with DCD made significantly more [finger word coordination] (*t*(22)=1.23, p=.23) and WM errors (*t*(22)=2.59, *p*=.02) than TD developing children. Indeed, children with DCD made almost four times more WM errors than children in the control group (79.5% vs 20.5% of all WM errors, respectively). Moreover, they were the only ones to make [finger word coordination] errors. All [finger word coordination] errors were produced by three children with severe fine motor skills impairment (Manual dexterity index respectively of P0.5, P1 and P9).

3.3 Biomechanical data

The four functionality indexes (i.e., *total duration, inter-finger transition, regularity* and *finger/voice synchronization* indexes) were analyzed to examine the functionality of finger movements during FC. Three tasks with different WM loads were analyzed: counting-like finger movement with no WM load, finger-counting with low WM load, and the N^{th}-After task with high WM load. Only the numerical condition of the N^{th}-After task was taken into account to make it comparable to the two control tasks. Moreover, the N^{th}-after task involved raising of 2 to 9 fingers, while the two control tasks required raising of all ten fingers. Given these methodological differences in data collection, the group effect was analyzed separately in each task.

In the counting-like finger movement task, three mixed-effect models were run to compare (1) total duration, (2) inter-finger transition and (3) regularity indexes across groups. For each of the three models, group was added as main predictor while participants and items were considered as random effects. Results revealed that neither total duration (SE=.02, *t*(52)=-1.89, *p*=.06), inter-finger transition index (SE=.12, *t*(52)=-1.89, *p*=.06), nor regularity (SE=.84, *t*(52)=-1.76, *p*=.08) were significantly predicted by group. These results suggest that the three functionality indexes did not differ between DCD and control group when the FC movements were performed without verbal recitation.

In the finger-counting task, four mixed-effect models were run to compare (1) total duration, (2) inter-finger transition indexes, (3) regularity and (4) finger/voice synchronization across groups. For each model, group was added as main predictor while participants and items were considered as random effects. Results revealed that group did not significantly predict neither total duration (SE=.19, $t(52)=.20$, $p=.84$), inter-finger transition (SE=.13, $t(52)=-.48$, $p=.64$), regularity (SE=.61, $t(52)=-1.12$, $p=.26$), nor the synchronization (SE=.10, $t(52)=-1.06$, $p=.29$). This indicate that the different functional parameters of FC were similar in children with DCD and in control participants.

In the N^{th}-After task, four mixed-effect models were run to compare (1) total duration, (2) inter-finger transition, (3) regularity and (4) finger/voice synchronization indexes across groups. For each model, group and item accuracy in N^{th}-After task (success *vs* failure) and the group-by-performance interactions were added in the model respectively as first-, second-, and cross-level predictors. Participants and items were treated as random effects. Neither the group (SE=.06, $t(237)=-.76$, $p=.45$), the performance (SE=.05, $t(237)=-.59$, $p=.59$) nor the interaction (SE=.04, $t(237)=-1.79$, $p=.08$) predicted the total duration. Likewise, the inter-finger transition index was not predicted by group (SE=.13, $t(237)=-.81$, $p=.42$), performance (SE=.09, $t(237)=-.81$, $p=.42$) or group-by-performance interaction (SE=.09, $t(237)=.81$, $p=.42$). Regarding the regularity of FC gestures, there was no evidence that group (SE=.31, $t(237)=.79$, $p=.43$), performance (SE=.26, $t(237)=.77$, $p=.43$) or interaction (SE=.28, $t(237)=.67$, $p=.50$) were significant predictors either. Finally, finger/voice synchronization was neither predicted by group (SE=.36, $t(237)=1.37$, $p=.17$), performance in the N^{th}-After task (SE=.24, $t(237)=.16$, $p=.87$), nor by group-by-performance interaction (SE=.25, $t(237)=.01$, $p=.99$). Altogether, these findings reflected that, children with DCD did not differ from their peers on execution speed, and inter-digital transition speed, regularity and finger/voice synchronization when using FC in a task with high WM load (N^{th}-After task) whether the answer given by the child was correct or not.

4 Discussion

The purpose of this study was to investigate the functionality of FC in children with DCD using behavioral and biomechanical data. At the behavioral level, we examined whether children with DCD use FC efficiently to solve a task with high WM load, named the N^{th}-After task. At a biomechanical level, different aspects of FC functionality were examined in the light of four parameters captured from 3D motion analysis to determine whether FC movements were as fast, regular and synchronized with voice in children with DCD as in typically developing children. Contrasting with the N^{th}-After task, FC movements were further examined in two control FC tasks with lower WM demands to determine whether FC functionality in each group was influenced by the WM demands of the task.

The results of behavioral analyses showed that, compared to control group, children with DCD were less accurate in the N^{th}-After task. This group effect was not modulated by the condition (i.e., letters or numbers), indicating that it was related to the task and not to the type of ordered sequence. As all children who participated reached the breakable chain level of knowledge for the alphanumeric sequences used in the study, the group difference could not be explained by a lower level of elaboration of these sequences in the DCD group either. Interestingly, when WM was added to the model, the group effect disappeared suggesting that WM could account for some part of the variance between groups. Indeed, the N^{th}-After task was designed to place heavy demands on WM so that FC was not only compulsory but also useful for the task at hand. To solve the task, the child had (1) to maintain instructions in WM, including the starting point and the number of fingers to be raised, and (2) to coordinate the finger raises with the sequence recitation to keep track of counting. In typically developing children, the use of fingers gives the WM sufficient room to ensure that these different processes run smoothly (Crollen, Mahe, et al., 2011). Here, analyses of errors reported in the N^{th}-After task showed that the most common errors in both groups concerned the maintenance of instructions (i.e., initiation or stop errors) and that these errors were almost four times more frequent in children with DCD. They could be related to their weaknesses in WM, an impairment which was reported multiple times in children with DCD (Alloway & Archibald, 2009; Lachambre et al., 2021; Sartori et al., 2021).

Interestingly, Dupont-Boime and Thevenot (2018) showed that 6-year-olds with low resources in WM make less use of FC to solve calculation than children with better resources. To explain this difference, the authors suggested that the discovery and the implementation of FC as a relevant strategy to solve addition would require high resource in WM. When these resources are lacking, WM can be overloaded by FC, leading children with limited resources to use other more error-prone strategies. For children with DCD who experience fine motor impairment (Barnett & Prunty, 2021; Biotteau et al., 2019; Huau et al., 2015), FC might be demanding, especially in dual-task situation. Indeed, when motor and cognitive tasks have to be handled simultaneously, children with DCD have been found to prioritize the cognitive task over the motor task, resulting in a degradation of their motor performance which could reflect a lack of automatization of motor processes (Laufer et al., 2008; Tsai et al., 2009). Similarly, the use of FC in the Nth-After task is a dual task situation which not only requires coordinating recitation and finger movements but also maintaining in WM the number where to start and the number of fingers to be raised. If FC is demanding in WM (i.e., FC movements are cognitively effortful, or, not enough automatized at a basic level), children with DCD might be pushed to commit an important amount of WM ressources in FC at the expense of the maintenance of intructions.

This assumption is called into question by the fact that biomechanical data showed no group differences on any of the functionality indexes in any of the task which required FC movements, whatever the WM demands (i.e., counting-like finger movements, finger counting and Nth-After). Even in the Nth-After task which makes the heaviest demand on WM, children with DCD produce FC movements that are as synchronized, as fast and as regular as their peers. Furthermore, although they were the only ones to make [finger word coordination] errors, these errors were a minority (n=11 out of 147 errors reported). Finally, item accuracy in the Nth-After tasks was not a significant predictor of any of the four functionality indexes, indicating that FC functionality was not related to item success or failure. Altogether, these results are inconsistent with the assumption that FC movements would be cognitively demanding for children with DCD. Indeed, high cognitive load seemed to have no significant impact on the functionality of the FC movements in children with DCD, suggesting that their FC movements might have reached a certain degree of automatization through practice since the beginning of kindergarten. However, it is still possible that children with DCD, equipped with the markers as they were in the motion lab, had prioritized FC and devoted available WM resources to finger movements, as required by the N^{th}-After task, to the detriment of the instructions to be held in WM, resulting in a large number of WM errors. Further researches will be necessary to examine FC automatization using experimental design contrasting different levels and types of working memory load.

To sum up, the present study failed to find functional limitation of FC gestures in children with DCD. However, the implementation of FC could have consumed resources in WM and could have led DCD children to commit more WM errors in a task with high WM load. Future investigations are needed to determine whether this pattern of results is also present in children with math learning disorders, or whether it is specific to children with DCD. A straight comparison with children with MLD in a task similar to the N^{th}-After task could be particularly interesting because, children with MLD seem to benefit from FC to compensate for their WM deficits in numerical processing (Noël, 2005, 2009; Passolunghi & Cornoldi, 2008), unlike children with DCD in the present study. Interestingly, the few FC errors were made exclusively by three children with DCD with severe fine motor impairment. Given that the cognitive profile of DCD children is very heterogeneous (Van Dyck et al., 2022), it is possible that some of them present difficulties severe enough to hinder effective finger-recitation coordination during finger counting. It would be interesting to compare different profiles in larger samples of children with DCD to determine whether certain profiles are more at risk of presenting finger-recitation coordination difficulties.

In conclusion, the current findings showed that children with DCD were less accurate than typically developing children in a FC task that put heavy demands on WM. The present results suggest that these difficulties could be more related to a limitation of WM resources than to dysfunctional FC gestures. This research is the first to investigate CF functionality in children with DCD using 3D motion analysis, an innovative technique providing a high level of a precision that could not be obtained through straight behavioral observations. The 3D motion analysis opens up many new perspectives on issues relating to embodied numerical cognition. In particular, this technique should make it possible to focus on the functionality of the gestures involved in numerical and arithmetical processing (FC and cardinal number gestures). Currently, studies that questioned the role of fine motor skills in mathematical cognition development focused on motor tasks that were far removed from the gestures performed in numerical contexts (i.e., pegboard, tying shoelaces, stacking cubes; for reviews see Barrocas et al., 2020; Neveu et al., 2023). From a functionalist point of view, future works should take a closer focus on fine motor skills which are more proximal to those used in numerical contexts to better understand their involvement in typical and atypical numerical and arithmetic development.

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Chapter 7 - Training arithmetical skills when finger counting and working memory cannot be used: A single case study in a child with cerebral palsy.

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CASE REPORT

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Abstract:

Children with cerebral palsy (CP) are at greater risk of mathematical learning disabilities due to associated motor and cognitive limitations. However, there is currently little evidence on how to support the development of arithmetic skills within such a specific profile. The aim of this single-case study was to assess the effectiveness of a neuropsychological rehabilitation of arithmetic skills in NG, a 9-year-old boy with CP who experienced math learning disability and cumulated motor and short-term memory impairments. This issue was explored combining multiple-baseline and changing-criterion designs. The intervention consisted of training NG to solve complex additions applying calculation procedures with a tailor-made computation tool. Based on NG's strengths, in accordance with evidence-based practice in psychology, the intervention was the result of a co-construction process involving NG, his parents and professionals (therapist and researchers). Results were analysed by combining graph visual inspections with non-parametric statistics for single-case designs (NAP-scores). Analyses showed a specific improvement in NG's ability to solve complex additions, which maintained for up to three weeks after intervention. The training effect did not generalize to his ability to perform mental additions, and to process the symbolic magnitude.

Keywords: case-control study; evidence-based practice; mathematical cognition; neurological disorders; learning disabilities; developmental age; motor disorders

1 Introduction

Cerebral Palsy (CP) is a permanent neurodevelopmental disorder caused by brain injuries that occur during the perinatal period or in the first months of life. Movements and postures of children and adolescents with CP are particularly affected and are often associated with neuropsychological disturbances such as intellectual disability (Reid et al., 2018), visuo-perceptual impairment (Schmetz et al., 2019) or attentional and executive difficulties (Craig et al., 2019). Academic achievement also appears to be affected (Gillies et al., 2018), with a significant proportion of children exhibiting specific learning disabilities (Frampton et al., 1998).

From the very beginning, children with CP exhibit poor number sense. They showed a lower ability to compare the number of elements in a set (de Freitas Feldberg et al., 2021), to rapidly estimate small numerosities (i.e. reduced subitizing range; Arp & Fagard, 2005) and to count (Lecointre & Camos, 2004). All of these basic numerical skills have been identified as precursors to future arithmetic skills in typically developing children (Jordan et al., 2009; Krajewski & Schneider, 2009; Watts et al., 2014) as well as in children with CP (Van Rooijen et al., 2015). At school they struggle with mathematics (Critten et al., 2018) and have been found to be less efficient in solving small additions and subtractions, especially when enrolled in special education (Jenks et al., 2007; Jenks, de Moor, et al., 2009; Jenks, van Lieshout, et al., 2009).

Typically, children learn to calculate through the implementation of finger counting strategies (Björklund et al., 2019) before giving way to mental computation with no concrete support (Jordan et al., 2008). Such a level of competence requires powerful working memory resources. Otherwise, it is impossible for the child to perform the task without fingers, or to solve complex arithmetical problems involving multiple resolution steps and the maintenance of intermediate results (LeFevre et al., 2005). Finger use also supports the development of the base ten system and provides a concrete support for number composition (Crollen & Noël, 2015; Roesch & Moeller, 2015). Fine finger movements are also required when using manipulatives, which are frequently provided as a concrete support within the classroom when teaching mathematical concepts (for meta-analysis see Carbonneau et al., 2013). These elements explain why fine motor skills prove to be a good predictor of typical arithmetic development (Asakawa & Sugimura, 2014).

With regards to this typical developmental sequence, the cognitive profile of children with CP involves several risk factors that could cumulatively contribute to the emergence of mathematics learning disabilities. First, they often suffer from fine motor skill impairments (Arnould et al., 2007), which puts them in a poor condition to use their fingers effectively. Moreover, they are more prone to visuo-spatial processing deficit and eye-hand coordination problems (Stadskleiv et al., 2018), resulting in difficulty to implement early quantification processes such as subitizing (Arp & Fagard, 2005) and counting abilities (Camos et al., 1998). Finally, children with CP often experience working memory impairment (Stadskleiv et al., 2018), leaving them with a long-lasting dependence on finger-based strategies and/or concrete support (Peng et al., 2015). In children with CP a substandard working memory was found to be predictive of mathematics learning disabilities (Jenks et al., 2012; Van Rooijen et al., 2016). However, their severe fine motor impairments usually prevent the efficient use of finger-counting or manipulatives, with no other options than solving calculation mentally with an overloaded working memory, which drastically increases the risk of errors.

To date, many mathematical interventions have been conducted in children and adolescents with learning disabilities (Jitendra et al., 2018) but only a handful have been set up specifically for children with CP. To the best of our knowledge, only two training studies have been conducted in children with CP: one targeted the child's motivation to improve arithmetic problem solving (Sheehey et al., 2017) while the other focused on the implementation of an interactive geometry software computer program to enhance angle knowledge (Shaw et al., 1998). To date, no study has ever examined how to enhance and support the development of arithmetic procedures in children with CP, in particular, those who cumulate motor and working memory impairment.

Current Study

The current study examined the effectiveness of an arithmetic procedural training with a specific equipment in a 9-year-old boy with spastic diplegia named NG. He experienced mathematical learning disabilities resulting in a persistent inability to calculate. In the context of his pathology, NG cumulated different risk factors including short-term memory and fine motor skills impairments, which prevented him from using finger-counting strategies or manipulatives to reduce working memory load during computation.

In accordance with Evidence-Based Practice (EBP), the intervention was designed to meet the needs of NG, using an equipment tailored to his abilities. This intervention is grounded in the four pillars of EBP: research, clinical expertise, patient characteristics and organizational context (McCurtin & Clifford, 2015) which were used as the guidelines in the co-construction process involving NG's parents, researchers and a speech therapist.

The main objective of the present intervention was to enable NG to solve Tens/Units + Tens/Units complex additions with carrying (e.g. 34+49), using a suitable equipment. Combining multiple-baseline and changing-criterion designs, the three main issues addressed in this single-case experimental study concerns (1) the training effectiveness, (2) the training specificity and (3), the generalization effects. First, training effectiveness should manifest as an improvement in NG's ability to solve complex additions accurately with his specific equipment. Second, training specificity should demonstrate that improvement in arithmetic problem solving is attributable to the training and not to general cognitive development. Finally, generalization effects should translate into an improvement in numerical tasks that were not directly trained but were nevertheless related to the intervention (i.e. ability to calculate with no equipment and Arabic number comparison).

2 Method

2.1 Design

The three issues were addressed using a combination of multiple-baseline and changing-criterion designs. In a changing-criterion design the training effectiveness is demonstrated when the target behaviors change positively throughout the different stages of the intervention. Here, the training was divided into five stages of increasing difficulty, in order to steer NG towards solving an increasing number of computational procedures. Altogether, these five stages were designed to enable NG to implement the complex procedures necessary to solving complex additions on his own. The transition from one stage to the next was determined by the achievement of a success criterion (i.e. at least 90% success rate during at least three consecutive training sessions), which required continuous repeated measures of the child's progress. Accordingly, problem solving accuracy was assessed daily by NG's mother using a three-point scale: (a) wrong response, 0 point; (b) right answer with assistance, 1 point; (c) right answer without assistance, 2 points. Assistance was considered from the first help of the adult, whether it was to orally guide NG in his reasoning or to support him in the handling of tools. Daily problem solving success rate was reported on evaluation sheets communicated to the therapist. During weekly therapy sessions the decision to move to the next stage was taken by the researchers and the speech therapist, in concertation with NG's mother, when the success criterion was reached, and if NG's fluency was deemed sufficient (i.e. absence of hesitation and slow response time). When NG met the success criterion several days before a weekly therapy session, consolidation sessions were conducted with a mix of calculations from the previous stages until the day of the therapy session, in order to keep him motivated.

In addition to the changing-criterion design, multiple-baseline design was conducted resulting in an assessment of several behaviors in NG, at different time points. In order to assess the intervention effects (i.e. training effectiveness, training specificity and generalization effects), baselines were conducted at three time points: (1) pre-test (= three days before the first training session), (2) post-test (= the day after the last training session), and (3) follow-up (= three weeks after the post-test session). Each baseline was repeated a minimum of three times at each time point. The sessions, conducted by the main investigator, took place in the family home setting, in the presence of NG's parents. Due to his attention deficit/ hyperactivity disorder, each assessment session was spread over two days, in blocks of tasks administered in 15- to 20-minute sessions. Instructions and items were presented on a computer except for the working memory task for which the instructions were given orally.

Before beginning data collection, NG and his parents were informed about the objectives of the research, the methodology and the training procedure. NG's parents completed an informed consent form and the child gave oral consent. This research project was approved by the local ethic committee (reference number 2021-090).

2.2 Case report

NG is a French-speaking boy aged 9 years and 4 months. He is an only child and lives alone with his parents. The family's socioeconomic status, collected using the International Standard Classification of Occupation (ISCO-08; International Labour Organization [ILO], 2008) is high, with both parents reporting intellectual and scientific occupations. NG has congenital spastic diplegia and microcephaly (brain lesion site unknown) associated with an attention-deficit/ hyperactivity disorder and a speech disorder. Despite use of Methylphenidate the sustained attention window remains limited.

After a first year of mainstream schooling, NG was enrolled in a special education school for children with motor disabilities, where he follows an individualized curriculum. Although delayed, NG exhibited better reading and writing skills than his classmates. In contrast, teachers noted great difficulties with mathematics and reported a significant and persistent delay in number sense development and calculation skills. Three years of unsuccessful instruction had led to NG developing severe anxiety in the mathematical learning situation, as reported by both teachers and parents. Faced with math avoidance, anxiety and (sometimes) oppositional behavior, teachers no longer knew how to approach new mathematical concepts with him.

A complete neuropsychological assessment was conducted before starting the intervention (Table 1). Motor latencies and fine motor skills assessment confirmed that NG had slower motor reaction times and a severe impairment in manual dexterity. Fluid reasoning and verbal comprehension were in the normal range[7] and were identified as strengths in NG's general cognitive profile, whereas visuo-spatial abilities were impaired. The assessment of working memory showed that verbal and visuo-spatial short-term memory skills were impaired while central executive remained in the normal range. NG was able to encode and store information in long-term memory but had difficulties in organizing his speech in a free recall session due to [a verbal dyspraxia. In NG, this disorder led to difficulties in articulating all the speech sounds, resulting in poor, jerky and disorganized spontaneous speech.][8]

Visual and auditory selective attention were in the normal range. Finally, lexical knowledge and reading comprehension development corresponded to the level expected in the second grade of elementary school[9].

The assessment of the mathematical cognition development (Table 2) confirmed the presence of mathematics learning disabilities. Knowledge of number sequence and counting skills could be considered as strengths. In contrast, the processing of Arabic number magnitude and the understanding of the numerical inclusion relationship was delayed. Arithmetical processing was severely delayed. Additions and subtractions with Arabic numbers were unsuccessful as soon as the second addend was greater than three. NG mainly used a *counting all* strategy in solving arithmetic problems but was rapidly limited by his reduced capacity in verbal short-term memory. Using finger-counting led to calculation errors, and calculating with manipulatives was inaccurate as tokens dropped frequently.

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[7] Performance is considered as within the normal range as long as it does not deviate more than 1.6 standard deviation below the reference mean (i.e. Percentile 50).

[8] Note that changes made to the submitted manuscript are marked with square brackets in the thesis text.

[9] Performance within the normal range for this school grade.

Table 1: Fine motor skills, motor latencies and general cognitive assessment (9 years and 4 months)

Functions and test	Raw score	Standard score
Global functioning (WISC V)		
Verbal comprehension	81	
Similitaries	18/46	ss 8
Vocabulary	13/54	ss 5
Visuo-spatial index	**69**	
Block design	10/58	**ss 4**
Visual puzzles	7/29	ss 5
Fluid Reasoning	74	
Matrix Reasoning	5/32	**ss 2**
Figure Weights	17/34	ss 9
Memory		
Questionnaire of memory (Q-MEM)		
Effortful intentional learning	27	z = 1.41[a]
Prospective memory/ organization	11	z = 0.12[a]
Working memory	25	**z = 4.59**[a]
Working memory		
Forward digit span (WISC-V)	4 - span 3	**ss 4**
Backward digit span (WISC-V)	7 - span 3	ss 9
Picture span (WISC-V)	11 - span 3	**ss 4**
Long term memory		
Story subtest (CMS)		
Total Free Recall	19/82	**ss 2**
Total Free Recall after delay	19/82	**ss 4**
Recognition	24/30	ss 8
Attentional functioning		
Alertness (TAP)		
RT without warning	407 ms	**P4**
RT with warning	315 ms	P14
Phasic alertness index	0.277	P95
Auditory selective attention		
Simple auditory task (TAP)		
RT	617 ms	P38
Omitted answers	0	>P38
Incorrect answers	1	P54
Visual selective attention		
Cancellation (WISC-V)		
Randomized order	19	ss 6
Structured order	18	**ss 4**
Error	0	
Total	37	ss 5
Fine motor skills (MABC-2)		
Checklist	54	**<P5**
Manual dexterity subtests for children from 3 to 6 years old		
Posting coins		Scale 3-3years and 5 months
Best hand (Left)	17s	ss 6
Other Hand	20s	ss 7
Threading Beards	**Impossible**	
Tracing trail	**Impossible**	

Note. z = z-score; ss = standard score; P = percentile; [a] reversed scale, performance interpreted as impaired when z-score ≥ + 1,66.

Table 2: Developmental profile in numerical and arithmetical tasks of the TEDI-MATH PETIT battery.

		Kindergarten		1st grade		2nd grade		3rd grade		
	Scores	**1st period**	**2nd period**	**1st period**	**2nd period**	**1st period**	**2nd period**	**1st period**	**2nd period**	**Maximum**
Number sequence	12/12									**x**
Counting	13/13									**x**
Knowledge of Arabic numeral system	17/20			100	19	<all				
Written numerical decision	8/8									**x**
Comparison of Arabic numbers	9/12			100	15	<all				
Knowledge of oral numerical system	27/39			100	79	57	<all			
Oral numerical decision	12/12									**x**
Judgement of grammaticality	10/12				100	29	3	4	<all	
Comparison of oral numbers	5/15			< all						
Base-10	5/27					< all				
Transcoding	31/40				100	23	<all			
Writing Arabic numbers	15/20				100	23	<all			
Reading Arabic numbers	16/20				100	27	<all			
Additive decomposition of numbers	0/6		100	8	<all					
Arithmetical operations										
With pictorial aids	4/6	42	18	7	<all					
Verbal problem solving	3/8	100	57	28	11	3	<all			
With Arabic numbers	10/40		100	47	5	<all				
Simple additions	5/12		100	46	12	<all				
Incomplete additions	0/8		100	28	4	4				
Simple subtractions	5/10		100	96	77	19	9	7	<all	
Incomplete subtractions	0/4		100	54	24	11	7	5	<all	

Note. This table provides normative scores corresponding to NG's performance (9 years and 4 months) in the numerical and arithmetical tasks from the TEDI-MATH standardized battery as a function of school grade and period of year. Data are expressed in cumulated percentages. <all = all children of the reference population scored higher than NG.

2.3 Intervention

The two main priorities identified for this intervention were knowledge of Arabic number sense and arithmetical skills. As the main request of the parents, teachers and speech therapist was to focus on calculation abilities, the principal target of the present intervention was complex addition solving. The present rehabilitation was tailored to overcome NG's cognitive impairments in short-term memory and fine motor skills while taking advantage of acquired knowledge identified as strengths (knowledge of number word chain, counting and transcoding). Accordingly, specific equipment was used to provide NG with a concrete support for computation and limit the impact of working impairment on his performance.

2.3.1 Materials

Preliminary step: finding a suitable tool. Prior to starting the therapeutic intervention, a preliminary step was conducted to determine which type of computational equipment NG would be most comfortable with. With this aim in mind, he was asked to solve additions under four conditions with different types of external media: mental computation (no media), finger-counting, abacus or hundred square (i.e. a mat with a 10x10 matrix, each cell numbered from 1 to 100 with Arabic numbers, see below for a complete description). [Finger-counting and the abacus were two media familiar to NG, since his teacher encouraged him to use them when solving calculations. NG child had never used the hundred square before]. NG was presented with a set of 18 additions divided into three levels of syntactic complexity: (1) six Unit+Unit additions (U+U additions; e.g. 3+4); (2) six Ten Unit+Unit additions (TU+U additions; e.g. 14+3) and (3) six Ten Unit+Ten Unit additions (TU+TU additions; e.g. 25+12). At each level, half of the operations involved a carry. The task was stopped when all calculations of the same syntactic level were incorrect. An accuracy score and a proximity score (i.e. score of deviation from correct answer) were calculated for each type of support. Non-overlap of All Pairs scores (NAP-scores) were calculated to compare performance (Parker & Vannest, 2009).

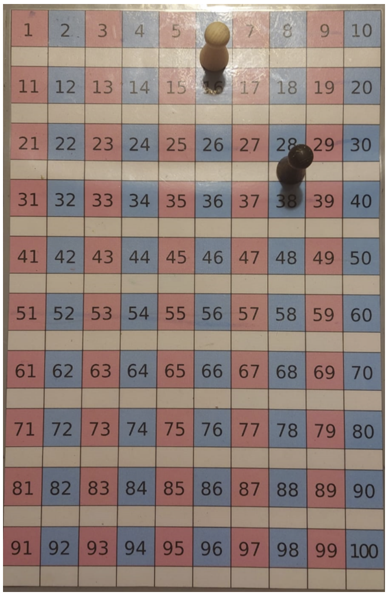
The results (Table 3) show that NG answers were significantly more accurate when using the hundred square in comparison with the three other conditions, with a really marked effect. The incorrect answers fell closer to the target (large effect size) when calculating with the hundred square in comparison with the three other tools. NG's incorrect responses were significantly less precise when using finger-counting than when using mental strategies, suggesting that finger-counting was particularly non-functional for him. Based on these results the hundred square was adopted as the main tool during the intervention.

Table 3: Results for addition problems solved in order to find the most suitable tool for NG.

Conditions	**Accuracy score (NAP)**				**Proximity score (1-NAP)**			
	Raw score (/16)	Fingers	Abacus	Hundred square	Raw score[b] (%)	Fingers	Abacus	Hundred square
Mental computation	2	.67	.67	1*[a]	53.32	0*	.11	1*[a]
Fingers	3		.50	1*[a]	78.22		.89	1*[a]
Abacus	3			1*[a]	60.56			1*[a]
Hundred square	11				16.13			

Note. NAP = Non-overlap of All Pairs index (NAP); *$p<.05$; [a] large effect size; [b] reversed scale, the best scores were reported by the smallest values.

Computational equipment. The intervention relied on a three-fold tailor-made computational equipment composed of different tools specifically designed to support the assimilation of different knowledge entailed in arithmetical reasoning (Figure 1). The first tool was the *hundred square*, a mat (dimensions: 30.5 x 20 cm) presenting a square of 100 cells organized into 10 columns and 10 rows. Each cell was numbered from 1 to 100 with Arabic numbers. The rows were separated by a 2 cm-wide white band. The hundred square was fixed to a metal plate, and two magnetic pawns were provided to facilitate manipulation and so that NG could handle them without dropping them. The second tool, two sets of ten magnetic Cuisenaire rods of different colors (2 cm wide) and segmented into units (2 cm-long intervals) were provided to represent the numbers from 1 to 10. The third tool was a magnetic whiteboard used to write instructions and reasoning during the exercises in order to reduce the cognitive load in WM to the highest possible degree.



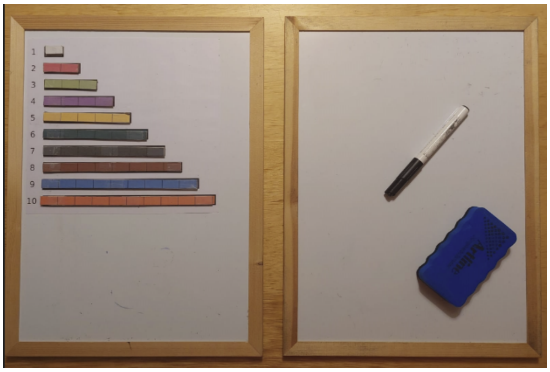


Figure 1: Computational equipment used during the intervention[10].

2.3.2 Training procedure

The present intervention was the result of an iterative process of co-construction involving the researchers and the speech therapist (hereafter referred to as *the professionals*) in addition to NG's mother. Each week, NG's mother participated in a 30-minute training session under the supervision of professionals in order to learn how to train NG to be successful at calculation exercises. Each session ended with a short mother-professionals debriefing (15 min) with the aim of defining how the exercises would be implemented ultimately at home. At home, NG participated in daily training sessions (10-15 min) guided by his mother with the purpose of assimilating the procedure and making it more precise and automatic with repeated practice. All sessions were recorded and shared online with the professionals. Online mother-professionals meetings were organized by request, with the purpose of debriefing about difficulties seen on the videos and in order to adjust the training procedures accordingly.

In accordance with the changing criterion design, the five stages of the intervention pursued specific sub-objectives of increasing difficulty. In stages 2 to 5, once the computation procedure had been completed, NG was encouraged to verbalize his reasoning, this was transcribed in real time by his mother onto the whiteboard. At each stage the final answer to each calculation had to be stated aloud by NG.

Stage 1- Identifying a targeted Arabic number on the hundred square. NG was given a two-digit Arabic number. He was trained to decompose the tens/units structure and to find the target number using a procedure relying on the hundred square organization (i.e. units presented horizontally, each row representing a ten, Figure 2a). After identifying the first digit (Tens), NG was invited to move his finger down the mat, from row to row, counting tens successively ("one ten, two tens…") until the number

[10] Note that the illustrations of the equipment have been modified in the present thesis compared to the published paper.

of tens was reached. From this point, he was trained to move his finger, from cell to cell, to the right, counting forward from the ten ("twenty-one, twenty-two, twenty-three…") until reaching and tagging the target Arabic number.

Stage 2- Solving (T)U+U additions with no carry. NG was given (T)U+U additions involving no carry and was invited to place the white pawn on the cell of the mat corresponding to the first operand of the addition, following the procedure of Stage 1. He was then taught to select the Cuisenaire rod corresponding to the second addend and to place this rod to the right of the pawn (Figure 2b). Finally, NG was trained to use a *counting-on* procedure to reach the correct answer.

Stage 3- Solving (T)U+U additions with carry. NG was given (T)U+U additions involving a carry and was trained to repeat the Stage 1 and 2 procedures until he noticed that the Cuisenaire rod came out of the mat, indicating that it was necessary to move the surplus on to the next ten. NG was then invited to map and replace this Cuisenaire rod (called the reference rod) by two shorter complementary rods representing the additive composition of the reference number (Figure 2c). To do so, NG was taught to determine the magnitude of the first rod by counting the number of units necessary to complete the ten (i.e. cells between the pawn and the end of the line). To determine the magnitude of the second complementary rod, NG was trained to place the first rod under the reference rod and to count the remaining units on the reference rod. Together, the cumulated magnitudes of both complementary rods had to be equivalent to the magnitude of the reference rod. Finally, NG had to place the first complementary rod to the right side of the white pawn, and to transfer the second to the beginning of the next row in order to reach the correct answer.

Stage 4- Solving TU+TU additions with no carry. NG was given a (T)U+TU additions with no carry and was asked to solve computations using Stage 1 and 2 procedures. He was trained to decompose the second addend in tens and units prior to the manipulations. Following the Stage 1 procedure, he placed the white pawn on the first addend on the hundred square. From the location of this white pawn, he was taught to add the tens of the second addend by moving a black pawn down, one row at a time, while counting the tens of the second addend ("one ten, two tens…"). From this new point, he was finally invited to select and place the Cuisenaire rod representing the unit of the second addend, following the Stage 2 procedure, to reach the correct answer (Figure 2d).

Stage 5- Solving TU+TU additions with carry. NG was given (T)U+TU additions involving a carry and was trained to combine the Stage 3 and Stage 4 procedures in order to move to the next ten using the additive composition. (Figure 2e).

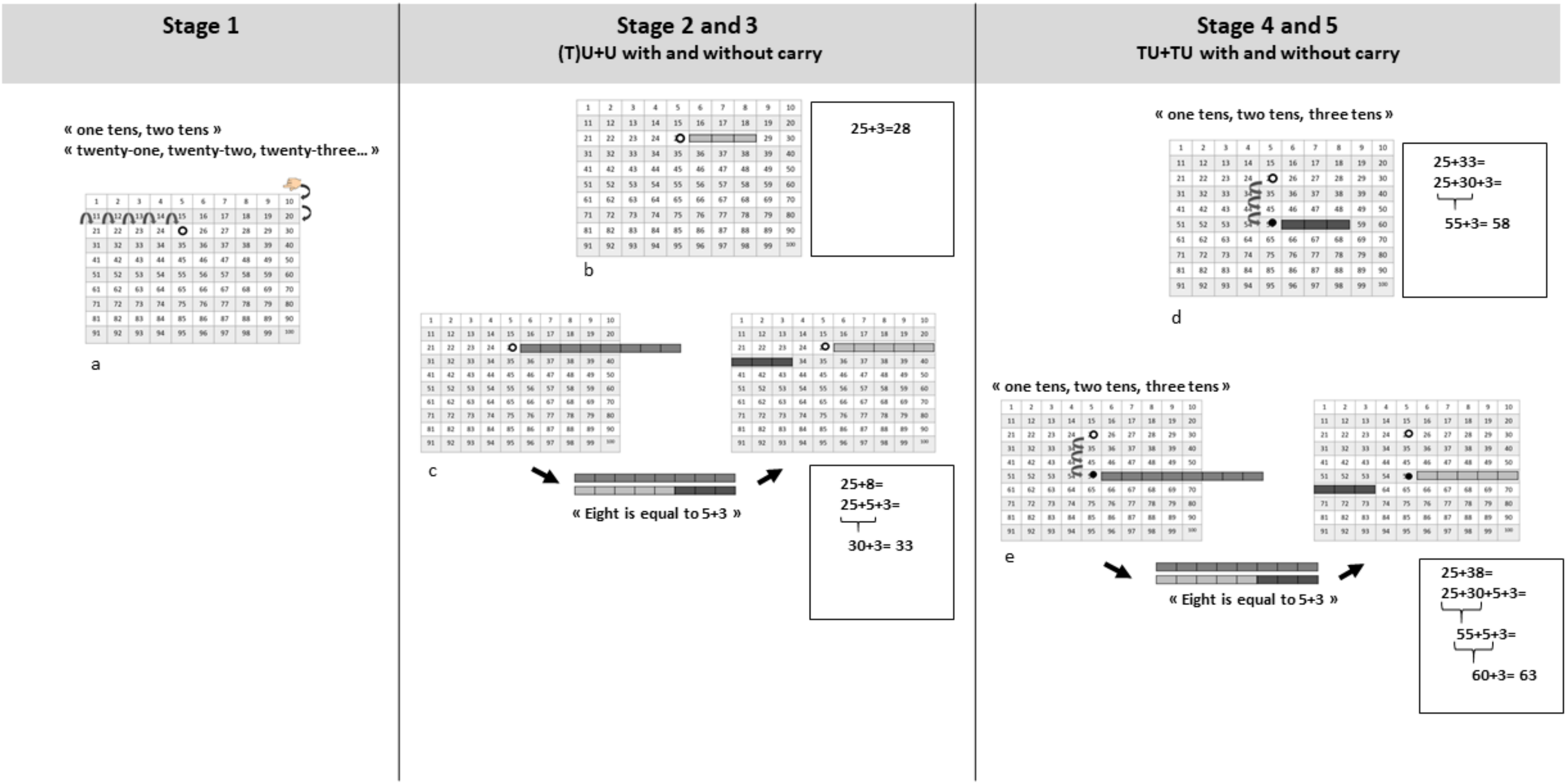


Figure 2: Illustration of the five stages of the intervention

2.4 Outcome measures

In addition to the repeated assessments performed in the changing-criterion design, pre-, post- and follow-up intervention assessments were conducted following a multiple-baseline design. Outcomes measures were divided into *target measures* assessing the effectiveness of the intervention, *control measures* examining its specificity and *transfer measures* investigating the generalization effects.

2.4.1 Target measures

Additions with tools. NG was presented with a set of six additions to be solved using the procedures he had been taught to use during his intervention with the three-fold computational equipment. The difficulty level of the calculations varied according to (1) the Ten-Unit syntax of Arabic numerals (Level 1: six U + U additions; Level 2: six TU+U additions and Level 3: six TU + TU additions) and (2) the presence of a carry (half of the additions involved a carry at each level). Responses were assessed using the same scale as used by NG's mother during daily home training sessions. No time limitation was imposed during the task.

2.4.2 Transfer measures

Additions with no tools. NG was presented with a set of six additions to be solved mentally without the computational equipment. He was simply asked to solve addition in his head and to say the result out loud. Additions were of the same complexity as in the task with equipment.

Arabic number comparisons. The processing of symbolic number magnitude was assessed using an Arabic number comparison task. NG was asked to read aloud two Arabic numbers (from 1 to 99) and to identify the larger one. He was presented with a set of 12 pairs of Arabic numbers with varying numerical distances: six close pairs (difference < 3) and six distant pairs (difference > 3). The syntactic structure of the two Arabic numbers to be compared was matched within each pair (same number of digits). Close pairs belonged to the same tens [(e.g., 24 *vs* 26)] while distant two-digit number pairs belonged to different tens [(e.g., 26 *vs* 47)]. Each correct answer was credited with one point.

2.4.3 Control measures

Subtraction fluency. The ability to solve small subtractions was evaluated using an arithmetical fluency task based on the Tempo Test Rekenen (De Vos, 1992). A set of 40 calculations of increasing difficulty were presented [orally] to NG. The difficulty varied according to the Ten (T)- Unit (U) syntax of Arabic numerals, the magnitude of the difference and the presence of borrowing. NG was asked to solve as many subtractions as possible in one minute, and to state the responses orally. Each correct answer was credited with one point.

Working memory. Working memory abilities were assessed using the backward digit span task inspired by the Working memory subtest of the WISC-V (Fidelity coefficient= .86;Wechsler, 2014). The stimuli consisted of a set of 18-digit sequences of increasing length (i.e. two to eight digits). The participant had to repeat, in reverse order, a digit sequence read aloud by the experimenter. Two training trials were administrated before starting the task. Each correct answer was credited with one point. The task stopped after two successive errors on same-length sequences.

2.5 Analyses

Results were analyzed by combining qualitative and quantitative approaches. Repeated measures taken during daily home training sessions were analyzed by visual inspections of the figures, as recommended for N-of-1 trials (Kazdin, 2021). Visual inspections were conducted in terms of trend (i.e. increase or decrease of correct response rate over a stage of interventions), shift (i.e. discontinuity in the correct response rate), latency of change and overlap of performance.

Repeated measures were complemented by pre- and post- intervention measures analyzed in two steps. Firstly, visual inspections were conducted comparing pre- and post- baselines (pre-/post- baselines) and comparing post- and Follow-Up baselines (post-/FU baselines) to therefore describe the overlap between performance and the direction of change occurring during the intervention and the maintenance phases. To complete and confirm visual analyses, two different measures of progression between time points were calculated to assess the training effect (pre- vs post-baselines) and the maintenance effect (post- vs FU- baselines). These measures were adjusted to the initial level of performance (Vanclay, 1991), on the basis of the following formula:

$$\text{Progression score} = \frac{(\text{endpoint success rate} - \text{initial success rate})}{\text{maximum of success rate} - \text{endpoint success rate})} * 100$$

Secondly, statistical analyses were conducted using a non-parametric approach consisting of calculating Non-overlap of All Pairs scores (NAP-scores, Parker & Vannest, 2009). Ranging from 0 to 1, NAP-scores close to .93, .66 and ≤.65 indicated respectively as large, moderate and weak effect (Parker & Vannest, 2009).

3 Results

3.1 Compliance with training

A few guidelines were defined to optimize compliance. Five training sessions had to be administered over the week at times convenient to the child. NG was asked to solve a minimum of five calculations per session, which were to be interrupted whenever he appeared inattentive or uncomfortable with the task demands. Additional training sessions could be conducted on NG's request. Compliance with training was high, with an average of 5.7 sessions conducted per week. Only 10% of the sessions had to be shortened.

3.2 Effectiveness of the intervention.

3.2.1 Repeated measures

Visual inspections of repeated measures specific to each stage show strong upward trends followed by a stabilization phase across sessions for stages 1, 2, 3, and 4 (Figure 3). This pattern of results was less obvious at Stage 5 where scores seemed stable, with a weak upward trend observed from session 47. Quantitatively, comparing performance between the first and last session, the scores increased by 50%, 50%, 75% and 75% during stage 1,2,3 and 4 respectively. Concerning stage 5, scores were stable (Improvement rate = 0%). NAP-scores confirmed these trends with significant changes of moderate range during stages 1 (*NAP-score*=.82*,* *p*=.03) and stage 3 (*NAP-score*=.75*,* *p*=.02) and of a wide range during stages 2 (*NAP-score*=.93*,* *p*<01) and stage 4 (*NAP-score*=.93*, p*<.01). Changes during Stage 5 were not significant (*NAP-score*=.61*, p*=.45), probably due to the fact that NG's scores were already high at the beginning of this stage.

3.2.2 Target measures

Concerning the pre-post assessment, visual inspection showed a positive change in additions with tools compared with pre/post baselines, as well as a maintenance of progress after a three-week timeframe. No overlap of performance was observed when comparing the pre/post baselines, whereas the post/FU baselines completely overlap (Figure 3). The results of the visual inspections were confirmed by a clear improvement of NG's performance when comparing pre/post baselines (Training effect = +100%) and a strict maintenance when comparing the post/FU baselines. The NAP-Score further confirmed these results (pre/post: *NAP-score*=1*, p*<.05; post/FU: *NAP-score*=0.5*, p*=1) with a significant change when comparing the pre/post-baselines (Table 4).

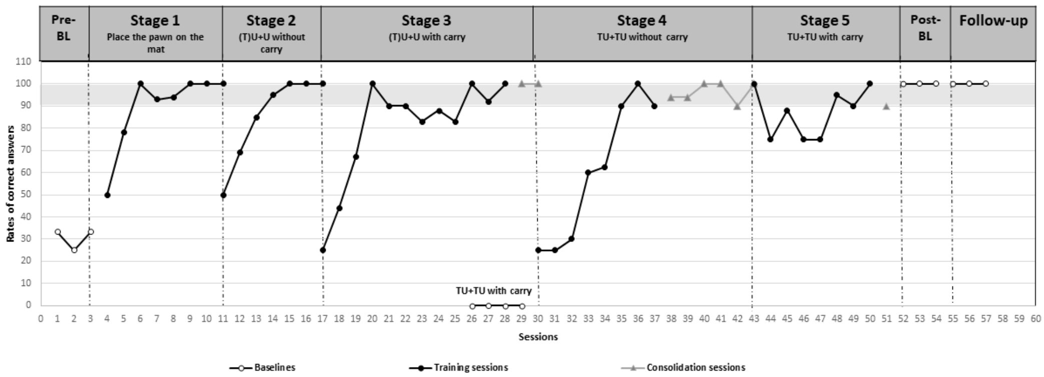


Figure 3: Rates of correct responses over the baselines, the five stages of the intervention and the maintenance. *Note*. BL= baselines.

3.3 Specificity of the intervention

Two methods were used to confirm that the changes observed in NG were attributable to the intervention, and not to aspecific factors. First, Figure 3 shows a close correspondence between the change in the criterion difficulty and NG's performance with respect to the specific objective of the stage (Kazdin, 2021). As depicted in Figure 3, NG's performance dropped sharply on three occasions just after an increase in the difficulty of the stage. Indeed, the performance dropped by 50% between stage 1 and 2, 75% between stage 2 and 3 and 75% between stage 3 and 4. No shift was observed between stages 4 and 5. In order to show the specific importance of stage 4 in achieving the pattern observed at stage 5, an intermediate assessment in solving TU+TU additions with carry (objective of stage 5) was conducted between session 26 and 29 (i.e. at the end of stage 3). Visual inspections reveal a positive change in scores between the intermediate baseline and stage 5, with no overlap of performance. Quantitative results show an important improvement of scores (Training effect = +87.2%) confirmed by a significant NAP-score with a significant change (*NAP-score* = 1*, p*<01). The procedures trained in stages 1 to 3 were not sufficient to reach the objective of the intervention (i.e. solve TU+TU additions with carry). Stage 4 was necessary in order give training in the missing procedure, to achieve the final objective and to generalize NG's knowledge of the procedure taught in stage 5.

A second way of examining the causal link between changes observed and the intervention was to demonstrate that these changes were not related to general cognitive development, nor to general numerical development. Regarding working memory measures, Figure 4a shows an overlap in performance between pre/post baselines and between post/FU baselines. Quantitative results reported in Table 4 demonstrate a slight decrease of working memory abilities between pre/post baselines (Training effect = -5.7%) and a maintenance of post-baseline performance after a three-week timeframe (Maintenance effect = +0%). However, the NAP-score indicated no significant changes in both situations (pre/post: *NAP-score*=.33, *p*=.51; post/FU: *NAP-score*=.50*, p*=1).

With regard to the subtraction fluency task, visual inspection of Figure 4a shows an overlap of performance when comparing pre/post baselines and comparing post/FU baselines. Quantitative results reported in Table 4 demonstrate a slight improvement of the score comparing pre/post-baselines (Training effect = +5.5%) and a small decrease when comparing post/FU baselines (Maintenance effect = -2.9%). However, the NAP-scores were not significant in either of the situations (pre/post: *NAP-score*=.78, *p*=.28; post/FU: *NAP-score*=.33*, p*=.51).

3.4 Generalization

Only pre- post- measures were conducted to assess the generalization of the skills taught during the intervention to other numerical domains. Visual inspections of performance in addition with no tools (Figure 4b) shows the same pattern of results in both pre- and FU-baselines. Several overlaps may be observed between the three sessions. Qualitatively, results show that scores decreased moderately when comparing the pre/post baselines (Training effect = -12.5%) and increased moderately when comparing the post/FU baselines (Maintenance effect = +11.1%). However, statistical analyses demonstrate no significant changes when comparing pre-, post- and FU baselines (Pre/post: *NAP-score*=.33*, p=.51*; post/FU: *NAP-score*=.67*, p=.51).* No significant changes, when comparing the three sessions, suggests a lack of a generalization effect of the ability to perform additions without equipment.

Regarding Arabic number comparison, Figure 4b shows a negative change between pre/post baselines with no overlap of scores and a stabilization of performance during the maintenance phase with an overlap of baselines. Quantitative analyses of results reveal a moderate decrease of performance comparing pre/post baselines (Training effect = -25%) and a small decrease comparing the post/FU baseline (Maintenance effect = -8%). Statistical analyses show that the differences were not significant (Pre/post: *NAP-score*=.11*, p*=.13; post/FU: *NAP-score*=.33*, p*=.51*).* No significant changes when comparing the three sessions suggests the lack of a generalization effect in the processing of symbolic magnitude.

Table 4: Summary of NG's results across phases**.**

Measures	Pre M (sd)	Post M (sd)	FU M (sd)	Pre/post		Post/FU	
				Training effect (%)	**NAP**	**Maintenance effect (%)**	**NAP**
Target measures							
Addition with tools	30.55 (4.81)	100 (0)	100 (0)	100	1*[b]	-	.50
Transfer measures							
Addition with no tools	11.11 (19.24)	0 (0)	11.11 (19.24)	-12.50	.33	11.11	.67[a]
Arabic number comparisons	44.47 (4.79)	30.57 (9.64)	25 (0)	-25.03	.11	-8.02	.33
Control measures							
Subtraction fluency	9.17 (2.89)	14.17 (6.29)	11.67 (3.82)	5.50	.78[a]	-2.91	.33
Working memory	35.19 (6.41)	31.48 (8.49)	31.48 (6.41)	-3.72	.33	0	.50

Note. Scores in success rate, FU= Follow-Up, NAP = Non overlap of All Pairs index, *$p<.05$, [a] Moderate effect size, [b] Large effect size

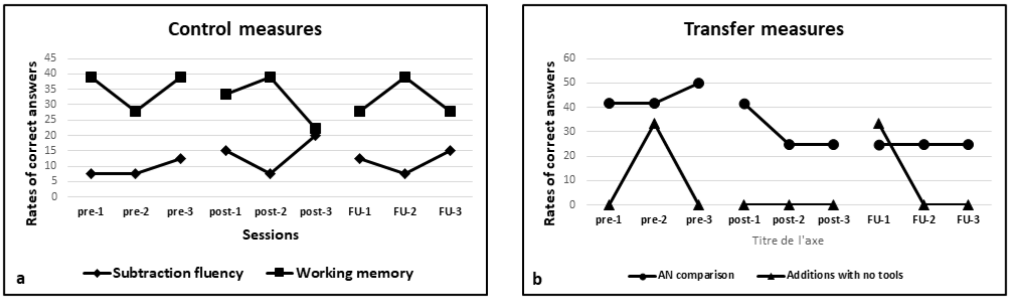


Figure 4: Evolution of transfer and control measures. *Note.* AN=Arabic Number

3.5 Social acceptability

To assess the compliance with training, a three-part survey was distributed to NG's parents after the intervention. In the first part, they were asked to rate on a 10-points scale their level of satisfaction with the therapeutic setting, the support received in implementing home training sessions, the time spent on the intervention and the materials. Overall, parents reported an average satisfaction of 90%. In the second and third parts of the survey, they were asked to rate on a 7-points scale, NG's academic skills development and on a 4-points scale, his behavior when confronted with mathematics. Regarding academic skills, parents reported an improvement of 86% in calculating with the tool, 57% on the ability to perform additive decompositions with Cuisenaire rods and an average improvement of 22% in numerical skills that were not directly trained (i.e. mental computation and processing of the magnitude of Arabic numbers). No improvement was reported for reading and writing skills. Regarding emotional and behavioral aspects, parents reported a 50% decrease in mathematics task avoidance, fearful behavior and self-depreciation in the home context. NG's acceptability of the treatment was also assessed during an interview conducted by the speech therapist based on four open questions. Firstly, NG was asked for his opinion on the system and he reported that he appreciated working with his mother and the professionals. He also indicated that he liked working with his hundred square because it helped him to calculate. Secondly, NG was asked to judge his own progression. He confessed that before the intervention it *was difficult to calculate*, he felt that he was *not good at maths*, he was *angry* and *afraid* (making throat noise), whereas after training he felt *it was simple* to calculate, he felt that he was *good at maths*, and *was not afraid anymore* when calculating.

4 Discussion

The present study aimed to assess the effectiveness of a training program designed to help a child with cumulative mathematical learning disabilities (MLD), impairment of fine motor skills and limited short-term memory resources, learning to solve complex additions using a computational tool composed of a hundred square and Cuisenaire rods. The specificity of the training program and the generalization to other untrained numerical domains were also questioned.

Data showed a large improvement in NG's ability to solve complex additions with the tailor-made equipment, followed by a maintenance up to three weeks after the rehabilitation had been stopped. The drop in NG's performance at each change of criterion, and the invariance of the control baselines (i.e. subtraction fluency and working memory) between the beginning and the end of the intervention, suggest that the improvements shown in the first four stages were due to a direct effect of the present intervention rather than a general developmental trend. The lack of any fall and the stabilization of performance observed in stage 5 appear to result from a generalization of the procedures trained during stage 1 through to 4, that specifically occurred at stage 4. Unfortunately, and contrary to what had been expected, no generalization was found in the ability to perform calculations without equipment, and additionally to the processing of the magnitude of Arabic numbers. NG's parents were satisfied with the intervention and reported a considerable improvement in their son's arithmetical skills in addition to a significant decrease in his anxiety and self-depreciation in a mathematical context.

Several factors related to the interventional design and therapeutic setting, implemented in accordance with EBP in psychology (McCurtin & Clifford, 2015), could have contributed to the success of the present intervention. Notably, the present rehabilitation was conducted using systematic and explicit instruction. This approach, based on Vygotsky's concept of the zone of proximal development (Vygotsky, 1978), is commonly recommended in special education for the teaching of mathematics to children with cognitive disabilities (Browder et al., 2008). It allows students to increase their learning in small steps, and to be guided during practice with the goal of achieving a high level of success. In the present case the target skill was divided into five sub-skills and the complexity of the exercises was gradually increased. Forward chaining procedures (i.e. procedures of increasing complexity built on to one another) were progressively integrated into the training schedule along with procedural verbal routines that supported mathematical thinking. Each time a new procedure was introduced the therapist accompanied the demonstration with clear instructions, so that NG could make connections between the different stages of reasoning. These elements, when combined, could have been particularly effective for NG as they promoted the transition at each stage between what he could do with assistance at the beginning to what he could ultimately do independently. As a result, NG was placed in a position that led to success at every stage of the intervention, which was highly beneficial towards fostering of his motivation, restoring his self-esteem and contributing to a sense of competence. Overall, this particular approach had a very positive influence on his mathematical anxiety and his general attitude towards the subject. Similarly, the lack of clear procedures and instructions making the explicit relationship between the ordinal position on the mat and numerical magnitude of numbers could explain why NG's knowledge did not generalize to the processing of the magnitude of Arabic numbers.

The triadic parent-child-professionals partnership was another active component of this training program. Unlike traditional interventions in which a therapist works alone with the patient, triadic interventions focus primarily on the parent, so that they can develop the skills necessary to support their child on a daily basis (Peterson et al., 2007). In this case NG's mother was present at every therapy session, to observe how the training was conducted with the therapist but also to suggest possible adjustments based on her own knowledge of the way her child works. Our results are consistent with previous studies showing the effectiveness of triadic intervention models (Salisbury & Cushing, 2013) assigned to how the professional accompanies the parent, but also how the parent interacts with the child at home (Barton & Fettig, 2013). In line with recommendations (McDuffie et al., 2013), child-mother interactions that took place at home were filmed and used during video-feedback sessions conducted at the behest of the mother, so that she could adjust her behavior according to her son's needs. In addition, the therapist-researchers collaboration has strengthened the therapeutic setting, deeply grounding the practices in both the scientific evidence and in the child's cognitive profile, by taking advantage of NG's strengths and reducing the effect of his impairment on his development. This therapeutic setting was highly beneficial to all parties: NG who emerged from the process with increased skills and confidence in maths, parents who have become more confident at coping with their child's difficulties and the therapist who has enriched their therapeutic toolbox with a higher level of evidence-based practice. This type of therapeutic framework, based on a close partnership between parents/patient and professionals, brings into question the current practice focused mainly on the patient, and should be promoted as a model for future mathematical interventions conducted with children identified as having MLD and, more widely, for neuropsychological interventions.

4.1 Limits and Perspectives

The current intervention was the first to show the effectiveness and the specificity of an arithmetical training program on a child with comorbid CP and MLD. By the end of the training NG had flawlessly mastered the procedures necessary to the resolution of complex additions with the tailor-made computational tools.

Similar to the others neuropsychological intervention studies, this research has some limitations. First, no explicit instructions other than those necessary to perform the trained procedures were given to the child. Therefore, NG was unable to generalize the tool usage to other numerical tasks, such as processing numerical magnitude. Moreover, at the end of training, NG was still dependent on the tool to calculate complex additions. Secondly, despite requests, there were few opportunities for interactions with educators from the special school in which NG is enrolled, thus limiting the partnership with the school.

Future avenues of specific work to lead NG to internalize the acquired procedure, and thus gradually discard the tool, should be initiated. This work should be supplemented with training focused on the memorization of arithmetic facts, as recommended in children with MLD in order to encourage abstract reasoning (Fuchs et al., 2008).

The objective of future training programs should also target NG's number sense by using the successor function. Due to his knowledge of the verbal number sequence, NG has learned to use equipment in a way that could be exploited with the goal of supporting his understanding of symbolic number magnitude, instead of his constant reliance on cardinal information, which has so far been unsuccessfully favored by teachers and therapist. Based on explicit instructions, NG could be trained to associate the position of Arabic numbers on the mat with their magnitudes, and thus compare the properties of ordinal numbers (i.e. units and tens represented in ascending order, from left to right and from top to bottom, respectively) instead of their cardinal values.

Finally, the parent-professionals therapeutic setting and partnership should be opened up even further to include educational establishment. Future research should encourage more collaboration between the educational teams that work with NG within the setting of his special school. This study found, similarly to previous studies conducted in children with developmental language disorder (Archibald, 2017), that promoting collaboration between therapists and educators is essential for therapeutic continuity; it enables the transfer of training on tools and procedures used in therapy, and at home, to within the classroom setting.

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Discussion générale

Remise en contexte

L'objectif principal de la présente thèse est de mieux comprendre la contribution des doigts au développement des compétences numériques et arithmétiques typique et atypique. Les questions qui portent sur le rôle des habiletés sensori-motrices (HSM ; i.e., habiletés motrices fines et gnosies) dans le développement numérique sont au centre de ce travail de recherche. Notre thèse s'articule en trois parties distinctes. Dans la première partie (**Chapitre 1 à 3**), un état des lieux des recherches menées à ce jour sur notre thématique a été proposé. Les études expérimentales conduites dans la deuxième partie de la thèse visaient à clarifier la contribution des HSM au développement des compétences arithmétiques typique ainsi que les processus sous-jacents à cette relation. Le rôle médiateur du comptage sur les doigts et de la maitrise des concepts cardinaux sur la relation HSM/arithmétique a été respectivement examiné dans l'étude longitudinale menée auprès d'enfants tout-venant suivis de l'âge de 6 ans jusqu'à 8 ans (**Chapitre 4**) et dans l'étude transversale conduite chez des jeunes enfants âgés de 3 à 5 ans (**Chapitre 5**). Les travaux menés dans la troisième partie auprès d'enfants présentant un déficit des HSM (i.e., trouble développemental de la coordination (TDC) et infirmité motrice cérébrale (IMC)) avaient pour objectif d'explorer les effets de leurs déficiences motrices sur leurs traitements numériques et de proposer, le cas échéant, des pistes d'interventions. La recherche conduite dans le **Chapitre 6** visait à investiguer la fonctionnalité du comptage sur les doigts chez les enfants ayant un TDC. Le **Chapitre 7** était, quant à lui, consacré à l'évaluation d'une rééducation du calcul menée auprès de NG, un enfant IMC présentant un handicap moteur important associé à un trouble des apprentissages en mathématiques et à un déficit en mémoire de travail. Nous proposons d'articuler notre discussion générale autour de trois questions transversales auxquelles nous répondrons par l'intégration de nos résultats aux données de la littérature actuelle. Les pistes de travail pour de futures recherches seront proposées au fil du texte.

Question 1 : Que nous apprend cette thèse sur les habiletés sensori-motrices ?

1 Les habiletés motrices fines

Alors que le terme d'habiletés motrices fines (HMF) est très largement repris dans la littérature, nous avons souvent rencontré des difficultés pour définir ce concept et déterminer à quelles compétences il se réfère. En examinant les études consultées durant notre thèse (voir Tableau 1 de l'Annexe 2 pour une synthèse) nous avons constaté que les auteurs s'accordent généralement pour définir les HMF comme *la capacité à contrôler les petits muscles de la main et des doigts* (e.g., Asakawa & Sugimura, 2022; Escolano-Pérez et al., 2020; Pitchford et al., 2016). Certains auteurs, ont une vision unitaire du concept d'HMF (e.g., Khng & Ng, 2021; Son & Meisels, 2006). Pour eux, le terme HMF se réfère à l'ensemble des habiletés motrices requises pour traiter les activités dans lesquelles la main et les doigts sont impliquées (e.g., utiliser des couverts, écrire…). Pour d'autres auteurs, en revanche, le terme HMF renvoie à un concept multi-déterminé qui regroupe plusieurs sous-catégories d'habiletés motrices évaluées distinctement pour déterminer l'implication de chacune d'elle dans le développement numérique (e.g., Fischer et al., 2022; Penner-Wilger et al., 2007; Pitchford et al., 2016). La première sous-catégorie se réfère aux habiletés motrices mobilisées pour manipuler des objets (sous-type 1). Reprise sous les termes « coordination visuo-motrice », « coordination motrice fine » « dextérité » ou « précision motrice fine », ces habiletés nécessitent une bonne coordination motrice en plus de compétences visuo-spatiales précises. La seconde sous-catégorie fait référence aux habiletés motrices nécessaires à la maitrise d'un outil scripteur utilisé pour reproduire une image ou pour écrire un texte (sous-type 2). Elle est référencée sous les termes « intégration visuo-motrice », « compétences grapho-motrices », « intégration motrice fine » ou encore « intégration visuo-spatiale ». Il s'agit là d'habiletés plus complexes que les précédentes puisqu'elles impliquent que l'enfant créer sa propre représentation mentale de la figure ou du texte à copier avant de mobiliser les séquences motrices qui lui permettront de retracer la figure ou de retranscrire le texte. Enfin, la troisième sous-catégorie, parfois nommée « agilité des doigts », renvoie aux habiletés nécessaires à la mobilisation individuelle des doigts, sans manipulation d'objet (sous-type 3). Beaucoup moins investiguée que les deux précédentes, cette catégorie a pourtant l'avantage d'isoler les compétences motrices des habiletés visuo-spatiales et grapho-motrices impliquées dans les deux catégories précédentes. Très fréquemment, le terme HMF est utilisé par les auteurs en référence à une des trois sous-catégories décrites ci-dessus. Le terme HMF peut alors faire référence aux compétences motrices impliquées dans la manipulation d'objets (e.g., Barnes et al., 2011; Gashaj et al., 2019) aussi bien qu'aux habiletés impliquées dans la mobilisation individuelle des doigts (e.g., Orrantia et al., 2022).

Dans le **Chapitre 5** de cette thèse, nous avons ciblé les HMF impliquées dans l'exécution des gestes de comptage (*HMF dynamique*) et des gestes numériques (*HMF statique*), évaluée par des analyses du mouvement en 3D. Alors que nous avions initialement présenté les *HMF dynamiques* et *statiques* comme deux construits différents, la forte corrélation entre les deux indices 3D obtenus (r=-.74) ainsi que la présence de multi-colinéarité dans nos analyses préliminaires nous a amené à remettre en question cette conception. Le manque d'indépendance entre ces deux facteurs laissait effectivement penser que les deux tâches utilisées pour évaluer ces HMF (i.e., reproduction de séquences motrices ordonnées et reproduction de configurations de doigts) faisaient appel à des habiletés motrices relativement proches. Les *HMF dynamiques* et *statiques* peuvent ainsi être considérées comme deux facettes d'un même construit que nous pourrions appeler *HMF spécifiques au comptage et aux gestes numériques* et qui pourrait s'intégrer dans la 3ème sous-catégorie d'HMF décrite plus haut (sous-type 3).

2 Les gnosies digitales

Contrairement aux HMF, le concept de gnosies digitales semble, lui, relativement bien défini dans la littérature. En effet, la synthèse des études consultées (voir Table 2 de l'Annexe 2 pour une synthèse) montre que l'ensemble des auteurs s'accorde à définir les gnosies digitales comme la *capacité à identifier et à discriminer ses propres doigts lorsqu'ils sont touchés en l'absence de feedback visuels* (e.g., Fayol et al., 1998; Noël, 2005; Wasner et al., 2016). Pour rappel, la tâche la plus classiquement utilisée dans la littérature pour évaluer les gnosies digitales consiste à cacher la main de l'enfant dans une boîte ou par un écran opaque avant d'exercer une pression sur l'un de ses doigts. Alors que la main est découverte, l'enfant est ensuite invité à identifier le doigt qui a été touché. Proposée pour la première fois par Benton et al., (1951), cette tâche a été intégrée, dès lors, dans de nombreux protocoles expérimentaux. Dans la majorité des recherches (e.g., Long et al., 2016; Malone et al., 2020; Noël, 2005), la tâche proposée se déroule en deux temps. Les premiers essais visent l'identification d'un seul doigt tandis que les essais suivants visent l'identification de deux doigts touchés simultanément ou séquentiellement. Pour résoudre la tâche, trois procédures différentes ont été identifiées. Dans certains cas, le participant est invité à montrer le doigt touché avec l'index de l'autre main. Alors qu'elle est très souvent employée (e.g., Gracia-Bafalluy & Noël, 2008; Newman, 2016; Penner-Wilger & Anderson, 2008), cette procédure présente l'inconvénient majeur de solliciter également des habiletés motrices fines ce qui pourrait entrainer un biais dans l'interprétation des données obtenues à partir de cette tâche. Pour se prémunir de cette éventualité, certains auteurs ont choisi de favoriser une approche n'impliquant aucun geste de la part de l'enfant (e.g., Fischer et al., 2022; Reeve & Humberstone, 2011; Wasner et al., 2016). Le dessin d'une main était alors présenté au volontaire. Après lui avoir touché un doigt, l'expérimentateur montrait un doigt sur le dessin et demandait au participant si « oui » ou « non » le doigt touché était le même que le doigt identifié sur le dessin. Avec ce type d'approche, l'enfant n'est confronté qu'à deux possibilités de réponse. La probabilité qu'il obtienne la bonne réponse en répondant au hasard est alors très importante (50%). Pour diminuer cette probabilité à 20%, nous avons choisi, dans le **Chapitre 4**, de colorier chaque doigt dessiné de manière à ce que l'enfant puisse résoudre la tâche en rappelant la couleur du doigt touché (Figure 1), offrant ainsi trois possibilités de réponses de plus que dans la méthodologie décrite précédemment. Pour les essais impliquant deux touches, cette probabilité chute même jusqu'à 5%, ce qui contribue à améliorer la validité de notre mesure.

Figure 1. Tâche évaluant les gnosies digitales utilisée dans le Chapitre 4.

Comme c'est malheureusement souvent le cas dans notre domaine de recherche, la qualité psychométrique des tâches utilisées pour évaluer les gnosies digitales a été très peu examinée par les auteurs. En effet, seuls quatre papiers sur les 12 consultés présentaient une mesure de fiabilité (i.e., fidélité test-retest ou consistance interne). La tâche proposée par Costa et al. (2011) s'avère être la plus fiable avec une consistance interne acceptable (KR-20 =.79). Dans deux papiers, les mesures traduisaient une fidélité test-retest (Noël, 2005; r=.50) ou une consistance interne (Wasner et al., 2016; α=.55) questionnable. La consistance interne de la tâche proposée par Fischer et al. (2022) peut même être considérée comme non acceptable (α=.39), ce qui traduit un manque d'homogénéité entre les différents items proposés dans la tâche. Tout comme dans le papier de Fischer et al. (2022), la tâche proposée dans le **Chapitre 5** de notre thèse souffre d'une faible consistance interne (α=.46). Pour rappel, cette tâche était constituée de 10 essais durant lesquels l'enfant était invité à identifier un seul doigt. Les cinq doigts de chaque main étaient alors testés. La faible consistance interne de cette tâche pourrait être due à la présence d'items plus simples à résoudre que d'autres. En effet, quatre items sur les 10 proposés impliquaient l'identification du pouce et de l'auriculaire, situés aux extrémités de la main. Plus saillants, ces doigts sont plus facilement identifiables que l'index et l'annulaire, souvent confondus avec le majeur. Dans le **Chapitre 4** nous avons proposé aux participants de résoudre une tâche constituée de 20 items. Similaire à la tâche proposée dans le **Chapitre 5**, les 10 premiers essais impliquaient l'identification d'un doigt. Les 10 essais suivants visaient la reconnaissance de deux doigts touchés séquentiellement. Dans cette deuxième phase, trois essais sur les cinq proposés impliquaient la reconnaissance de deux doigts distants de deux positions sur la main (i.e., séparés l'un de l'autre pas un doigt ; e.g., index et annulaire) homogénéisant ainsi la difficulté des items proposés. Cet aspect pourrait avoir contribué à l'amélioration de la consistance interne de notre tâche avec un Alpha de Cronbach acceptable (α=.69) et meilleur que ceux présentés dans les recherches précédentes. Les futurs travaux devront néanmoins veiller à continuer à améliorer la qualité psychométrique de cette mesure. Pour cela, les auteurs devront assurer une homogénéité entre les items proposés. A l'instar de la méthodologie proposée par Reeve et Humberstone (2011), une première approche pourrait être de sélectionner les doigts qui devront être identifiés par l'enfant de manière à ne garder que les doigts séparés par des distances équivalentes (e.g., pouce, index et annulaire) et éviter ainsi les effets de saillance du pouce et de l'auriculaire. Pour les essais impliquant la reconnaissance d'un seul doigt, une autre possibilité serait de doubler les items impliqués dans l'identification de l'index, du majeur et de l'annulaire de manière à diminuer le poids des items portant sur les doigts situés aux extrémités de la main (voir le travail de fin d'étude de Vossius (2018) pour une tâche similaire).

3 Relation entre habiletés motrices fines et gnosies digitales

A ce jour, on en sait très peu sur la relation qui unie les habiletés motrices fines et les gnosies digitales. A notre connaissance, seuls deux études conduites dans notre champs de recherche ont examiné cette relation chez l'enfant (Asakawa & Sugimura, 2022; Fischer et al., 2022). Toutes deux montrent l'existence d'une corrélation significative entre les gnosies digitales et la capacité à manipuler des petits objets (*r*=.46, Asakawa & Sugimura, 2022 ; *r*=.20, Fischer et al., 2022), chez des enfants âgés de 3 à 5. Une faible corrélation (significative) a également été montrée entre les gnosies digitales et la capacité à mobiliser les doigts individuellement (*r*=.19, Fischer et al., 2022). Ces résultats ne semblent pas surprenants si nous considérons les gnosies digitales comme un prérequis aux habiletés motrices fines. Nous pourrions alors penser que, pour manipuler des petits objets ou pour mobiliser précisément ses doigts, le jeune enfant doit avoir une bonne conscience de sa propre main et de ses doigts, donc de bonnes gnosies digitales. Contrairement à ce qui a été observé dans les papiers de Fischer et al. (2022) et Asakawa et Sugimura (2022), aucune corrélation significative n'a été mise en évidence entre les gnosies digitales et les HMF (r=.17), dans le **Chapitre 5** de notre thèse. Dans la discussion de ce papier, nous avions suggéré que ces résultats contradictoires pourraient s'expliquer par la faible consistance interne de la tâche utilisée pour évaluer les gnosies digitales dans ce protocole. Pour déterminer si ces résultats contradictoires peuvent être interprétés comme la conséquence d'un biais méthodologique ou s'ils reflètent effectivement une absence de relation entre les HMF et les gnosies digitales, un modèle de croissance latent complémentaire a été conduit à partir des données obtenues dans notre étude longitudinale (**Chapitre 4**). Ce modèle vise à examiner la valeur prédictive du développement des gnosies digitales sur l'évolution des HMF. Les résultats montrent qu'à 6 ans, les gnosies digitales sont significativement liées aux HMF (β=.33, S.E= .14, p=.02). En revanche, le développement des gnosies digitales ne semble pas prédire significativement l'évolution des HMF entre l'âge de 6 et de 8 ans (β=-.22, S.E= .16, p=.18). En accord avec les travaux de Fischer et al. (2022) et de Asakawa et Sugimura (2022) conduits chez des enfants âgés de 3 à 5 ans, ces résultats suggèrent que les gnosies digitales et les HMF semblent liées chez les jeunes enfants (3-6 ans) avant de suivre des trajectoires développementales indépendantes, soutenant l'idée d'un biais méthodologique dans notre **Chapitre 5**. Une hypothèse explicative pourrait être que les gnosies soutiendraient les HMF entre 3 et 5 ans, alors que les gestes fins, peu automatisés, impliquent un contrôle moteur important. A partir de 6 ans, la réalisation de gestes fins pourrait dépendre d'autres habiletés motrices telles que la proprioception par laquelle l'enfant conscientise la position de ses doigts dans l'espace, reconnue comme une condition préalable au geste des enfants âgés de 6 à 11 ans (Hay et al., 2005). De futures investigations restent toutefois nécessaires pour tester et confirmer cette hypothèse.

En bref, qu'avons-nous appris sur les habiletés sensori-motrices (HSM), grâce à la présente thèse ?

- Le terme d'HMF renvoie à un concept général qui regroupe 3 sous-catégories d'habiletés motrices (manipulation d'objets, compétences grapho-motrices et mobilisation individuelle des doigts). Le terme HMF est souvent utilisé pour désigner l'une de ces trois sous-catégories.

- Les *HMF statique et dynamique* sont probablement deux facettes d'un même concept que nous pourrions appeler *HMF spécifiques au comptage et aux gestes numériques* et qui pourrait être classifié dans la 3ème sous-catégorie d'HMF.

- Le concept de gnosies digitales est bien défini mais les tâches utilisées pour les évaluer sollicitent souvent des HMF ce qui pourrait biaiser l'interprétation des résultats obtenus à partir de ces tâches.

- La qualité psychométrique des tâches utilisées pour évaluer les gnosies digitales est peu investiguée par les auteurs. Lorsqu'elle l'est, les mesures utilisées dans les protocoles sont souvent de faible qualité.

- En l'état actuel de nos connaissances, les gnosies digitales semblent être liées aux HMF entre 3 et 6 ans. A partir de 6 ans, ces deux habiletés sensori-motrices semblent suivre des trajectoires développementales différentes.

Question 2 : Que nous apprend cette thèse sur la contribution des HSM aux compétences arithmétiques typiques et sur les mécanismes qui sous-tendent cette relation ?

Pour répondre à cette seconde question, nous nous réfèrerons aux résultats des études menées dans les **Chapitre 4 et 5**. Une lecture développementale de nos résultats vous sera proposée pour rendre compte de la contribution des habiletés motrices fines et des gnosies digitales aux compétences arithmétiques, à différents stades du développement de l'enfant tout-venant.

Bien que peu nombreuses, les études menées jusqu'à maintenant chez les enfants âgés de 3 à 5 ans et scolarisés à l'école maternelle, suggèrent un apport significatif des HSM sur le développement des compétences arithmétiques. Chez les enfants de 5 ans, les habiletés motrices fines (HMF) expliquent une part unique de la variance des compétences arithmétiques (Barnes et al., 2011). L'évaluation des HMF à 4 ans permet également de prédire le développement des compétences arithmétiques, deux ans plus tard (Asakawa & Sugimura, 2014). Dans leur récente recherche, Asakawa et Sugimura (2022) ont établi que, tout comme les HMF (r=.54), les gnosies digitales (r=.51) étaient corrélées aux compétences arithmétiques chez les enfants de 5 ans, une fois la mémoire de travail et l'âge pris en compte. Considérées ensemble, ces deux HSM expliquent une part additionnelle de 30% de la variance des habiletés arithmétiques, après avoir tenu compte de la mémoire de travail et de l'âge. La principale limite de la recherche proposée par nos collègues japonais découle du fait qu'à aucun moment, la part explicative de chacune de ces deux HSM n'a été définie. Dès lors, il est difficile de déterminer si ce sont les HMF ou les gnosies digitales qui contribuent majoritairement au développement des compétences arithmétiques des jeunes enfants. Les analyses statistiques proposées dans le **Chapitre 5** de la thèse, ont été conduites afin de dépasser cette limite. Conformément aux résultats obtenus par Asakawa et Sugimura (2022), nos analyses de corrélations ont montré que les gnosies digitales ainsi que les HMF étaient significativement liées aux compétences arithmétiques des enfants de 3 à 5 ans, une fois l'effet de l'âge contrôlé (corrélations respectives : r=.40 et r=.48). A elles deux, les gnosies digitales et les HMF expliquaient une part additionnelle de 22% de la variance des habiletés arithmétiques, après avoir considéré l'âge. Lorsqu'une analyse en Stepwise ciblant ces deux HSM a été conduite, nous avons constaté la perte de significativité de la part explicative des gnosies digitales au profit des HMF, traduisant un apport majoritaire des HMF aux compétences arithmétiques précoces. En somme, l'ensemble des résultats obtenus dans les études conduites chez les jeunes enfants de maternelle suggèrent que tant les HMF que les gnosies digitales supportent le développement des compétences arithmétiques précoces. Au-delà de la capacité à discriminer ses propres doigts (gnosies digitales), ce sont surtout les aptitudes à les mobiliser avec précision (HMF) qui semble contribuer majoritairement au développement arithmétiques des enfants de maternelle.

A l'heure actuelle, on en sait peu sur les mécanismes qui sous-tendent la relation entre les HSM et les compétences arithmétiques, chez les jeunes enfants. Une des principales hypothèses proposées par les auteurs serait que l'utilisation des doigts contribuerait au développement arithmétique des enfants de maternelle par l'apprentissage des habiletés numériques précoces (i.e., comptage verbal, cardinalité et énumération[1]). En 2022, Asakawa et Sugimura ont ainsi montré que le comptage verbal joue un rôle médiateur dans la relation existante entre les HMF et les compétences arithmétiques, chez les enfants de 5 ans. En maternelle, le comptage sur les doigts est souvent utilisé pour accompagner la récitation de la chaine numérique verbale. La mise en correspondance terme-à-terme entre un doigt levé et un mot-nombre récité aiderait les enfants à séquencer la chaine numérique verbale en percevant chaque mot-nombre comme une entité distincte (Bender & Beller, 2011). Le recours aux doigts supporterait ainsi l'élaboration de la chaine numérique verbale, un prédicteur particulièrement important du développement arithmétique (Lê & Noël, 2021). En effet, pour recourir aux stratégies de calcul basé sur le comptage (i.e.,

[1] Les compétences d'énumérations sont requises pour déterminer le nombres d'éléments qui se trouvent dans une collection. Pour résoudre la tâche, l'enfant utilisent les procédures de dénombrement pour traiter les collections de grande traille (>4) ainsi que le subitizing pour traiter des petites collections (<4).

comptage tout, *comptage sur* et *comptage min.*), l'enfant doit être en mesure de dissocier chaque mot-nombre de la séquence numérique. Autrement dit, il doit avoir atteint, au minimum, le niveau d'élaboration de la chaine *insécable* (Fuson et al., 1982). Le **Chapitre 5** de cette thèse vient harmonieusement compléter les travaux d'Asakawa et Sugimura (2022) en montrant que les HMF contribuent aux compétences arithmétiques des enfants de 3 à 5 ans par la maitrise des concepts cardinaux. A cet âge, les enfants sont souvent amenés à utiliser des gestes numériques pour représenter le cardinal d'un mot-nombre (e.g., lever le pouce, l'index et le majeur pour représenter « trois »). Comme ils jouissent à la fois d'un statut symbolique (i.e., facilitant l'accès à la sémantique du nombre) et d'un statut iconique (i.e., le nombre de doigts levés correspond aux nombres d'éléments de la collection ; cf. Chapitre 2, p.42), ces gestes numériques permettraient aux jeunes enfants de créer des ponts entre les mots-nombres et les quantités qu'ils représentent, supportant ainsi l'apprentissage de la cardinalité (Di Luca & Pesenti, 2008). Prédicteur important du développement arithmétique (Chu et al., 2018; Scalise & Ramani, 2021), la maitrise de la valeur cardinale des mots-nombres est indispensable à l'enfant pour comprendre les principes de la *fonction de succession* par lesquels il appréhende ses premières notions d'addition et de soustraction (Sarnecka & Carey, 2008; Sella & Lucangeli, 2020). Enfin, les résultats du **Chapitre 5** suggèrent que les HMF ne supportent pas les habiletés arithmétiques précoces par l'intermédiaire des compétences d'énumération (i.e., impliquant le dénombrement et le subitizing). Ces résultats paraissent contradictoires avec la recherche menée par Fischer et al (2017) au cours de laquelle les HMF ont été montrées comme étant significativement associées aux compétences de dénombrement d'enfants de 5 ans. Alors que nos collègues allemands ont proposé une tâche de dénombrement impliquant des collections de grandes tailles (de 5 à12) qui requièrent l'utilisation systématique du pointage, la tâche d'énumération proposée dans notre protocole impliquait également des items qu'il était possible de résoudre sans recourir aux doigts. Ceci pourrait expliquer en partie la divergence des résultats obtenus dans ces deux recherches. Une seconde hypothèse explicative pourrait tenir de la mesure choisie pour évaluer les HMF dans notre protocole puisque seules les composantes motrices impliquées dans le comptage sur les doigts ou l'exécution des gestes numériques ont été prises en considération. Comme le pointage ne requière aucune de ces habiletés motrices complexes, une absence d'association entre les HMF et les compétences d'énumération n'est donc pas surprenante. Mises ensemble, ces évidences expliquent ainsi plus clairement en quoi les HSM contribuent significativement au développement des compétences arithmétiques des enfants de 3 à 5 ans.

Assez curieusement, vers l'âge de 6 ans, nous constatons un changement dans ce pattern de résultats. C'est, en tous cas, ce que laisse à penser la recherche menée dans notre **Chapitre 4**. En effet, la conduite de modèles de croissance latents sur nos données longitudinales a montré qu'à 6 ans, seules les gnosies digitales étaient liées aux compétences arithmétiques. Par ailleurs, considérées ensemble, les gnosies digitales évaluée à 6 ans et l'évolution de cette habileté entre 6 et 8 ans expliquaient une part importante (43%) du développement des compétences arithmétiques. Aucune valeur prédictive des HMF n'a alors pu être mise en évidence, dans cette recherche. Ces résultats s'accordent avec ceux obtenus dans de précédentes études au cours desquelles il a été montré que les gnosies digitales étaient significativement liées aux compétences arithmétiques d'enfants de 6 à 10 ans (Fayol et al., 1998; Newman, 2016; Penner-Wilger et al., 2007; Wasner et al., 2016; Zhang et al., 2020). Les gnosies digitales évaluées à 7 ans s'avèrent également être de bons prédicteurs du développement des compétences arithmétiques, évaluées 15 mois plus tard (Noël, 2005). Une relation causale entre ces deux variables a d'ailleurs été établie dans une étude d'intervention menée chez des enfants de 6 ans et au cours de laquelle une amélioration des compétences arithmétiques a été constatée suite à un entrainement moteur visant à améliorer les gnosies digitales (Gracia-Bafalluy & Noël, 2008; voir Schild et al., 2020 pour des résultats contradictoires).

Pour mieux comprendre les mécanismes qui sous-tendent la relation gnosies/arithmétiques chez les enfants de primaire, nous avons proposé, dans notre **Chapitre 4**, de tester l'hypothèse fonctionnaliste selon laquelle les gnosies digitales contribueraient au développement des compétences arithmétiques par l'utilisation de stratégies de comptage sur les doigts. Nous avons alors été contraints de rejeter cette hypothèse puisque l'utilisation des doigts n'était corrélée ni aux gnosies digitales ni aux performances arithmétiques évaluées aux différents temps de mesure[2]. Ces résultats peuvent s'expliquer par une utilisation peu fréquente des doigts par les enfants, dans la tâche arithmétique (i.e., les doigts ont été utilisés pour résoudre 15 à 20% des items traités). Aucune évolution significative de la fréquence d'utilisation de ces stratégies n'avait, par ailleurs, été constatée dans le temps ce qui rendait impossible l'intégration de cette variable dans les modèles de croissance latents. Une hypothèse alternative avait alors été proposée selon laquelle, entre 6 et 8 ans, les gnosies digitales pourraient contribuer au développement des compétences arithmétiques par la reconnaissance de patterns de doigts. Cette hypothèse était alors fondée sur deux recherches menées récemment. La première ayant établie que la reconnaissance des patterns de doigts canoniques (i.e., conformes aux habitudes de comptage ; e.g., pouce, index et majeur levés pour représenter « trois ») évaluée à 6 ans est un bon prédicteur du développement arithmétique, évaluée 6 mois plus tard (Kreilinger et al., 2021). La nature structurée des patterns canoniques pourrait alors aider les enfants à affiner leurs connaissances des quantités en facilitant la compréhension des principes de composition et décomposition du nombre (Kreilinger et al., 2021; Kullberg & Björklund, 2020), une compétence importante pour le développement arithmétique. La seconde ayant démontré l'existence d'une corrélation significative entre les gnosies digitales et la reconnaissance de patterns de doigts canoniques, chez les enfants de 5 ans (Van Rinsveld et al., 2020). Cette corrélation ne nous semble pas surprenante si l'on considère que la reconnaissance de ce type de patterns implique d'identifier individuellement chaque doigt levé et de les localiser sur la main, deux habiletés qui supportent également les gnosies digitales.

Nous aimerions profiter de la discussion générale de notre thèse pour aller un pas plus loin dans l'investigation de notre hypothèse alternative en vous présentant brièvement les résultats d'analyses préliminaires conduites à partir des données longitudinales du **Chapitre 4**. Par ces analyses, nous cherchons à déterminer si (1) les gnosies digitales

[2] Pour rappel, les enfants de notre étude longitudinale ont été évalués à l'automne et au printemps de la première (T1 et T2) et de la deuxième année (T3 et T4) de primaire.

sont spécifiquement liées à la reconnaissance de patterns de doigts et si (2) la reconnaissance de ces patterns est également liée aux compétences arithmétiques, deux conditions préalables à la conduite d'analyses de médiation qui pourront être menées pour tester plus avant cette nouvelle hypothèse. Dans cette recherche, en plus des tâches évaluant les gnosies digitales, les HMF et les compétences arithmétiques, nous avions proposé aux participants de résoudre une tâche de reconnaissance de patterns de doigts durant laquelle ils étaient invités à indiquer, le plus rapidement possible, le nombre de doigts levés. Les patterns étaient présentés sur un écran d'ordinateur. Pour limiter le recour au dénombrement, chaque photo n'était présentée aux enfants que 500 ms. La tâche était composée de 16 items impliquant 1 à 9 doigts. La moitié de ces items étaient des patterns canoniques. Chaque item a été présenté deux fois, dans un ordre aléatoire. Les enfants étaient invités à répondre oralement. Un point leur a été attribué à chaque réponse correcte. Le temps entre le moment où l'image s'affiche à l'écran et la réponse de données par l'enfant était enregistré. Tout comme Van Rinsveld et al. (2020) l'ont fait dans leur recherche, un indice de reconnaissance de patterns de doigts a été calculé en divisant le nombre de réponses correctes par le temps de réponse. Seuls les indices calculés à partir des patterns canoniques ont été pris en considération dans les analyses.

Les résultats obtenus à partir de nos tâches ont été analysés par des corrélations de Pearson. En premier lieu, les gnosies digitales apparaissent comme étant corrélées avec la reconnaissance de patterns de doigts à chaque temps de mesure, sauf au T2 (T1 : r=.40, p<.001 ; T3 : r=.39, p=.001 ; T4 : r=.32, p=.01). Les gnosies digitales sont également liées à la reconnaissance des patterns de doigts évaluée à des temps ultérieurs (Gnosies T1 x Reconnaissance T3 : r=.31, p=.01 ; Gnosies T2 x Reconnaissance T3 : r=.29, p=.02 ; Gnosies T2 x Reconnaissance T4 : r=.25, p=.04 ; Gnosies T3 x Reconnaissance T4 : r=.36, p=.003). Contrairement aux gnosies digitales, aucune corrélation significative n'a été montrée entre les HMF et la reconnaissance de patterns de doigts aux différents temps de mesure (T1 : r=.13 ; T2 : r=-.08 ; T3 : r=.16), sauf pour le T4 où la corrélation est de faible intensité (r=.26, p=.03). Les HMF au T1 sont liées à la reconnaissance de patterns au T3 (r=.27, p=.03) et au T4 (r=.31, p=.01). Enfin, la reconnaissance de pattern de doigts est significativement liée aux compétences arithmétiques évalués à chaque temps de mesure, sauf au T1 (T2 : r=.30, p =.02 ; T3 : r=.33, p=.003 ; T4 : r=.28, p=.02). La reconnaissance de pattern au T1 est liée aux compétences arithmétiques évaluées aux T2 (r=.26, p =.03), T3 (r=.45, p <.001) et T4 (r=.25, p =.04). Enfin, la reconnaissance de patterns au T3 est associée aux compétences arithmétiques au T4 (r=.31, p =.01). Considérés ensemble, ces résultats traduisent une association significative entre les gnosies digitales et la reconnaissance de patterns de doigts, entre l'âge de 6 et de 8 ans. Cette association semble relativement spécifique puisqu'à l'exception du T4, la reconnaissance de patterns ne semble pas associée aux HMF. Cela suggère que la capacité à identifier précisément et rapidement les patterns de doigts canoniques serait principalement supportée par les représentations que les enfants ont de leurs doigts et de leurs mains plutôt que par la capacité à les mobiliser. Comme la reconnaissance de patterns de doigts est également associée aux compétences arithmétiques, cette variable apparait comme un candidat idéal pour médier la relation entre les gnosies digitales et les compétences arithmétiques.

En somme, les résultats obtenus dans les **chapitre 4 et 5** suggèrent que les habiletés motrices fines et les gnosies digitales seraient des composants clef du développement arithmétique. Entre 3 à 5 ans, les habiletés arithmétiques semblent davantage liées aux aptitudes à mobiliser les doigts (HMF) qu'aux aptitudes à des discriminer (gnosies digitales). A cet âge, les HMF supportent le comptage sur les doigts et les gestes numériques qui contribuent au développement des habiletés numériques précoces, eux-mêmes précurseurs du développement arithmétique. Vers l'âge de 6 ans, ce pattern change puisque seuls les gnosies digitales apparaissent comme étant un prédicteur significatif du développement arithmétique, alors évalué entre 6 et 8 ans. A ce stade de développement, l'hypothèse fonctionnelle selon laquelle les gnosies digitales soutiennent le développement arithmétique par le recours au stratégies de comptage sur les doigts est écartée. Une hypothèse alternative possible serait que les gnosies digitales supporteraient l'internalisation de représentations basées sur les doigts qui contribueraient, à leurs tours, au développement des compétences arithmétiques. De futures investigations doivent toutefois encore être conduites pour vérifier cette hypothèse.

Les études menées dans le chapitre 4 et 5 ouvrent de nombreuses perspectives pour de futures recherches. La contribution des patterns de doigts canoniques à l'apprentissage de l'arithmétique pourrait être ainsi être examinée dans une étude d'intervention qui viserait à examiner si le caractère structuré de ces patterns facilite l'apprentissage du calcul. La comparaison avec un autre support structuré tel que les configurations de points pourrait permettre de spécifier l'apport des doigts au développement du calcul. L'utilisation des analyses du mouvement en 3D pourraient, par ailleurs, être utilisées dans de futurs protocoles de recherche qui exigent une mesure fine des habiletés motrices impliquées dans les gestes de comptage et les gestes numériques. Couplées à d'autres outils de mesure tels qu'un micro et un eye-tracking, les analyses en 3D offrent de nombreuses possibilités pour mesurer des comportements difficilement quantifiables par de simples observations. A titre d'exemple, le recours à cet outillage pourrait permettre aux chercheurs de déterminer précisément la fréquence à laquelle les enfants regardent leurs doigts dans une tâche de calcul. Les mesures oculaires pourraient être couplées aux analyses 3D pour déterminer avec exactitude le moment où le regard se pose sur les doigts ainsi que le déplacement du regard durant le geste.

En bref, qu'avons-nous appris sur la contribution des HSM au développement des compétences arithmétiques, grâce à notre thèse :

Entre 3 et 5 ans :

- Les gnosies digitales ainsi que les habiletés motrices fines contribuent aux compétences arithmétiques précoces. Les aptitudes motrices (HMF) expliquent une part plus importante de la variance des habiletés arithmétiques que les aptitudes sensorielles (gnosies digitales).

- Les habiletés motrices impliquées dans le comptage sur les doigts et les gestes numériques (*HMF statique et dynamique*) contribuent aux compétences arithmétiques par la maitrise des concepts cardinaux. La relation HMF/arithmétiques n'est pas médiée par les compétences d'énumération.

De 6 à 8 ans :

- L'évolution des gnosies digitales expliquent une part importante du développement arithmétique (43%) en début de primaire. Aucune valeur prédictive de l'évolution des HMF n'a pu être mise en évidence.

- La relation gnosies/arithmétiques ne peut pas être expliquée par le recours à des stratégies de comptage sur les doigts efficaces. Plus que les aspects procéduraux, cette relation pourrait davantage être influencée par les aspects représentationnels du comptage sur les doigts. Cette hypothèse devra être testée dans de futurs travaux.

Question 3 : Que nous apprend cette thèse sur les répercussions d'un déficit des HSM sur les traitements numériques et sur les stratégies d'intervention envisageables pour atténuer les effets d'un tel déficit ?

Pour répondre à cette dernière question, nous nous réfèrerons aux résultats des études menées dans les **Chapitre 6 et 7** auprès d'enfants ayant un trouble développemental de la coordination (TDC) ou une infirmité motrice cérébrale (IMC). Avant de discuter les résultats de ces deux études, nous aimerions nous arrêter un instant sur les critères d'inclusion des études menées chez les enfants TDC afin de proposer quelques recommandations qui pourront guider la conduite de futurs travaux.

Bien que peu nombreuses, la majorité des études menées chez les enfants TDC dans le champ de la cognition numérique établit leurs critères d'inclusion à partir des critères diagnostiques du DSM-5 (i.e., l'enfant doit présenter une déficience motrice (critère a) persistante (critère c) qui interfère avec les activités de sa vie quotidienne (critère b) et qui n'est pas mieux expliquée par une déficience intellectuelle ou une déficience visuelle imputable à une affection neurologique (critère d); e.g., Alloway & Archibald, 2009; Gomez et al., 2015; Pieters et al., 2015). Après avoir exclu la présence d'une déficience intellectuelle ou visuelle, les habiletés motrices des enfants sont généralement évaluées en utilisant la batterie standardisée de la MABC-2. Dans certains travaux, le score-seuil utilisé pour cibler les enfants TDC se situe au percentile (P) 15 ou 16 (Gomez et al., 2015, 2016; Pieters et al., 2015), ce qui parait discutable. En effet, en utilisant un tel score, les auteurs ne ciblent pas uniquement des enfants qui présentent une déficience motrice mais également ceux qui ont des difficultés motrices, au risque de rendre l'interprétation de leurs résultats moins spécifique. Pour atténuer ce biais, nous avons choisi, dans notre **Chapitre 6**, de restreindre notre score-seuil au P9 afin de cibler des enfants qui ont des difficultés motrices très importantes et déficitaires. Toutefois, si nous souhaitons nous assurer que les résultats de nos études soient spécifiquement applicables aux enfants TDC, un score-seuil établit au P5 est fortement recommandé de manière à cibler les enfants avec une déficience sévère, comme Sartori et al. (2021) le propose dans leur recherche. De manière intéressante, ces auteurs ont également questionné les parents quant à la persistance des troubles de leurs enfants. Très peu pris en considération dans les travaux conduits dans le domaine de la cognition numérique, ce critère devrait davantage être évalué dans nos protocoles pour nous assurer que les difficultés observées chez les enfants à un instant t sont effectivement le reflet d'un déficit persistant et non de difficultés passagères. Les données de notre étude longitudinale (**Chapitre 4**) illustre le caractère occasionnel de ces difficultés, chez certains enfants. Alors que 24% des participants de notre échantillon présentaient un indice de dextérité manuel (MABC-2) égal ou inférieur au P5 à 5.6 ans, ils n'étaient plus que 19% à 7.7 ans. Six enfants, dont les habiletés motrices fines étaient considérées comme déficitaires à 5.6 ans, sont donc parvenus à rattraper leur retard dans les deux années qui ont suivies l'évaluation. A ce titre, nous recommanderions aux auteurs d'éviter l'inclusion d'enfants sur base d'un diagnostic posé plusieurs mois, voire plusieurs années avant la conduite de la recherche. Une évaluation systématique des habiletés motrices devrait être conduite au moment de l'étude afin de s'assurer que les enfants inclus dans les groupes TDC présentent une déficience persistante en motricité fine.

Pour mieux comprendre les répercussions d'un tel déficit sur les traitements numériques, nous avons investigué, dans le **Chapitre 6**, la fonctionnalité du comptage sur les doigts des enfants TDC. Nous avions alors avancé l'hypothèse selon laquelle les troubles moteurs de ces enfants pourraient réduire leur capacité à utiliser leurs doigts pour soulager leur mémoire de travail, dans une tâche à forte charge cognitive (N^{th}-After). Les gestes de comptage exécutés lors de la tâche N^{th}-After avait été comparés à ceux utilisés dans deux tâches à faible charge cognitive (levée des doigts, comptage de 1 à 10) afin de déterminer si l'augmentation de la charge cognitive de la tâche pouvait détériorer les gestes de comptage chez les enfants TDC. Alors que les enfants TDC étaient moins performants dans la réalisation de la tâche N^{th}-After que les enfants tout-venant, aucune mesure biomécanique n'a permis d'établir un dysfonctionnement des gestes de comptage chez eux, quelques soit la charge cognitive de la tâche proposée. Les erreurs observées chez les enfants TDC tenaient principalement à une limitation de leurs ressources en mémoire de travail entrainant des oublis massifs de consignes. En conséquent, nous avions rejeté notre hypothèse de départ. A l'issue de cette recherche, il reste encore difficile d'établir avec certitude que les déficits moteurs des enfants TDC n'interfèrent pas avec leurs gestes de comptage puisque deux hypothèses restent plausibles pour expliquer nos résultats. Au premier abord, nous pourrions penser que les gestes de comptage sont suffisamment fonctionnels et automatisés chez les enfants TDC pour ne pas interférer dans leurs traitements numériques. Il parait toutefois également envisageable que les enfants TDC aient consacrés une majeure partie de leurs ressources en mémoire de travail pour exécuter des gestes de comptage précis, au détriment des consignes données, ce qui pourrait expliquer le nombre important d'erreurs liées à des oublis de consignes. De futures investigations devront encore être conduites si nous souhaitons faire toute la lumière sur cette question. Dans de futurs protocoles de recherche, nous pourrions, par exemple, comparer les performances des enfant TDC à celles d'enfants tout-venant dans une tâche à forte charge cognitive avec et sans recours au comptage sur les doigts. La comparaison des performances des enfants TDC à celles d'enfants présentant des troubles des apprentissages en mathématiques pourrait, par ailleurs, être particulièrement intéressante car ces derniers semblent bénéficier du comptage sur les doigts pour compenser leurs déficits en mémoire de travail dans les traitements numériques (Noël, 2009; Passolunghi & Cornoldi, 2008).

Si aucune preuve ne nous permet d'affirmer que les déficits en motricité fine des enfants TDC interfèrent dans leurs traitements numériques, la situation semble tout à fait différente chez NG, l'enfant IMC avec lequel nous avons travaillé dans notre étude de cas **(Chapitre 7)**. Atteint d'une quadriplégie spastique impactant fortement ses HMF, NG présentait également un déficit en mémoire de travail associé à un trouble des apprentissages en mathématiques se manifestant par de grade difficultés à traiter les magnitudes des nombres arabes, à comprendre les relations d'inclusion numérique et à résoudre des calculs impliquant des opérandes supérieurs à 3. Lors de la première évaluation, les calculs proposés étaient résolus mentalement en utilisant la stratégie du *comptage tout*, rapidement limitée par la faible mémoire de travail de l'enfant.

L’utilisation de supports externes visant à soulager sa mémoire de travail et à matérialiser les termes des opérations proposées était fortement entravée par son handicap moteur. Pour compter sur ses doigts, NG utilisait une gestuelle stable mais peu conventionnelle puisqu’elle impliquait de combiner à la fois du comptage et des gestes numériques. Ainsi, NG levait respectivement le pouce, l’index et l’auriculaire pour accompagner la récitation des trois premiers mots-nombres. Les mots-nombres ‘quatre ‘ et ‘cinq’ étaient, quant à eux, accompagnés de gestes numériques impliquant respectivement l’index, le majeur, l’annulaire et l’auriculaire puis l’ensemble des doigts de la main. L’enfant n’utilisait que sa main dominante, répétant ainsi la gestuelle pour les mots-nombres de ‘six’ à ‘dix’. Par une observation plus attentive de ces gestes, nous avons également pu constater une désynchronisation doigt/voix impactant la mise en correspondance terme-à-terme des mots-nombres avec leurs doigts respectifs. Dans ces conditions, il est rapidement apparu que NG n’était pas en mesure de bénéficier du comptage sur les doigts dans la résolution de calculs. Le recours au matériel concret de manipulation tels que des jetons était également problématique puisque cela impliquait que NG puisse isoler deux collections de jetons pour matérialiser les termes de l’opération avant de dénombrer l’ensemble. Très laborieuse, cette stratégie s’est rapidement avérée inefficace puisque les jetons utilisés tombaient régulièrement par terre suite aux mouvements spastiques de l’enfant. Par ailleurs et conformément à ce qui a été observé chez d’autres enfants et adolescents IMC (Camos et al., 1998; Lecointre & Camos, 2004), le dénombrement des jetons disposés aléatoirement sur le table était lent et peu précis. NG commettait, en effet, de nombreuses erreurs d’omission et de répétition de cibles. L’utilisation d’un boulier s’est également avéré inefficace puisqu’il arrivait à NG de déplacer deux billes à la fois, faussant ainsi le nombre d’éléments impliquées dans le calcul. Pour conduire notre intervention, le choix s’est donc porté sur un matériel organisé et facilement manipulable par l’enfant : une matrice de 100 cases organisées en 10 lignes et 10 colonnes, complétée par des réglettes Cuisenaires aimantées.

L’intervention conduite dans notre **Chapitre 7** visait à améliorer les compétences arithmétiques de NG, par l’utilisation d’un matériel numérique adapté à son handicap moteur. Etant donné le profil de ce patient, le choix de cet objectif pourrait paraitre surprenant, au premier abord. En effet, lors de notre bilan, nous avions noté que l'enfant était en difficulté pour traiter les nombres arabes, traduisant un accès déficitaire à la représentation des magnitudes numériques, à partir de ces symboles écrits. Comme la maitrise des magnitudes numériques est un prédicteur important du développement arithmétique (e.g., Honoré & Noël, 2016; Scalise & Ramani, 2021), d'aucun se serait attendu à ce que la rééducation proposée à NG porte prioritairement sur cette habileté. Envisagé en premier lieu, cet objectif a toutefois été écarté car il ne répondait ni aux demandes de NG, ni aux attentes de ses parents et de l'équipe éducative qui l'accompagnait. En classe, au cabinet ou à la maison, tous les interlocuteurs rencontrés rapportaient un sentiment d'impuissance face à l'anxiété que NG pouvait manifester lorsqu'il était confronté à la résolution de calculs. Privilégiant une pratique clinique ancrée dans l'Evidence Based Pratice (EBP) (McCurtin & Clifford, 2015), nous avons choisi d'accéder aux demandes de NG et des différents intervenants en ciblant notre intervention sur un apprentissage procédural du calcul, de manière à permettre à NG de reprendre rapidement confiance en lui. Cette approche était alors considérée comme une porte d'entrée pour accéder à une meilleure compréhension du nombre. En effet, comme NG devait utiliser quotidiennement le tapis de 100 pour résoudre ses calculs, nous espérions qu'il apprendrait rapidement à associer la magnitude des nombres arabes à leurs positions sur le tapis. L'enfant aurait alors été en mesure de comprendre que la magnitude du nombre augmente de 1 unité à chaque déplacement sur la droite du tapis et de 10 unités à chaque déplacement vers le bas, les plus grands nombres se situant en bas à droite. Malheureusement, et contre toute attente, NG n'a pas été en mesure de faire cette association durant notre intervention. La comparaison de deux nombres arabes était encore très faible à l'issue de la rééducation, et ce même lorsque NG était invité à utiliser le tapis. Notre intervention a toutefois permis à NG de s'approprier ce nouvel outil sur lequel nous avons fondé la suite de notre prise en charge.

Notre étude d'intervention ouvre de nombreuses perspectives pour la conduite de futures interventions auprès d'enfants présentant un trouble des apprentissages en mathématiques avec ou sans déficience motrice. Les dispositifs thérapeutiques impliquant les parents devraient être davantage investigués puisqu'ils contribuent à aider le parent dans la compréhension de son enfant et dans son accompagnement quotidien. Par ailleurs, l'utilisation du tapis de 100 offre de nombreuses possibilités pour les prises en charge ciblant la compréhension des magnitudes symboliques écrites. L'étude des nombres dans un contexte ordinal pourrait alors parfaitement compléter les approches cardinales plus classiquement proposées. Le tapis de 100 pourrait enfin être proposé dans le cadre des prises en charge portant sur la compréhension de la base-10 puisque sa nature matricielle offre à l'enfant une visualisation aisée des unités (cases) contenues dans chaque dizaine (ligne).

En bref, qu'avons-nous appris, grâce à notre thèse, sur les répercussions des déficits des HSM des enfants TDC et IMC sur leurs traitements numériques et sur les stratégies d'intervention envisagées auprès de ces enfants ?

- Lorsqu'ils doivent traiter une tâche numérique impliquant une forte charge en mémoire de travail, les enfants TDC sont moins performants que leurs pairs au développement typique.

- Les difficultés des enfants TDC semblent être davantage imputables à leur déficit en mémoire de travail qu'à leurs déficiences motrices. Les gestes de comptage exécutés par les enfants TDC sont tout à fait comparables à ceux des enfants tout-venant, quelques soit la charge cognitive de la tâche traitée.

- Lorsque le déficit moteur est important, comme c'est le cas chez NG, il peut affecter l'utilisation du comptage sur les doigts et du matériel de manipulation classiquement utilisé pour représenter les termes des opérations. Les enfants doivent alors utiliser le calcul mental, ajoutant une difficulté à ces enfants qui présentent souvent de faibles ressources en mémoire de travail.

- Parce qu'elle était adaptée aux besoins de NG et co-construite avec ses parents et sa thérapeute, l'intervention proposée dans le Chapitre 7 a été un succès. De tels dispositifs thérapeutiques doivent être encouragés dans les pratiques cliniques conduites auprès d'enfants à besoins spécifiques.

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Conclusion générale

A l'heure où l'utilisation des doigts par les enfants fait encore l'objet de débats chez les enseignants et les scientifiques, la présente thèse a été conduite afin de mieux comprendre *la contribution des doigts dans le développement des compétences numériques et arithmétiques typique et atypique*. L'étude des HSM (i.e., gnosies digitales et habiletés motrices fines) était au cœur de ce projet de thèse composée de quatre études expérimentales. Entre 3 et 5 ans, nos résultats ont montré que les HMF étaient liées aux compétences arithmétiques par la maitrise des concepts cardinaux. A cet âge, même si les deux HSM sont significativement liées aux compétences arithmétiques des enfants, les HMF semblent être un prédicteur plus important que les gnosies digitales. A partir de 6 ans, ce pattern de résultats change puisque seules les gnosies digitales apparaissent comme étant un prédicteur significatif du développement arithmétique évalué jusqu'à l'âge de 8 ans. Il n'est pas possible d'expliquer la relation gnosies/arithmétique par l'utilisation de stratégies de comptage sur les doigts. Alors qu'ils présentent des HSM déficitaires, les enfants TDC semblent davantage limités par leur mémoire de travail que par leurs déficiences motrices pour traiter une tâche numérique à forte charge cognitive. Les troubles moteurs de ces enfants ne semblent pas affecter leurs gestes de comptage. Ce n'est que lorsque la déficience motrice est très importante, comme c'est le cas chez NG, que les gestes de comptage ainsi que le recours au matériel de manipulation sont affectés. Il est alors difficile pour ses enfants de s'appuyer sur un support externe pour matérialiser les nombres impliqués dans les traitements numériques, soulageant par la même occasion une mémoire de travail souvent déficitaire. Des interventions conçues à partir d'un matériel adapté à l'enfant, tel que nous l'avons proposé dans cette thèse, pourront être conduites. La relation triadique parents-chercheur-thérapeute devra être privilégiée pour garantir des prises en charges de qualité, ancrées dans les quatre piliers de l'EBP. Par son contenu particulièrement riche, notre thèse ouvre de nombreuses perspectives pour la conduite de futures recherches investiguant des questions tant fondamentales que cliniques.

Annexe 1 – Scoping review supplementary materials

Table S1, Part 1: Search strategy - Ovid PsycINFO (All).

	Search term(s)	Results retrieved
1	Calculus/	755
2	Algebra/z	1648
3	Mathematics/	13967
4	“Mathematics (Concepts)”/	4118
5	Mathematics Achievement/	7973
6	Mathematics Education/	12607
7	Mathematical Ability/	7371
8	Number Comprehension/	1514
9	Number Systems/	737
10	“Numbers (Numerals)”/	3470
11	(Calculus or Calculati*).ti,ab,id.	19097
12	Algebr*.ti,ab,id.	5691
13	Math*.ti,ab,id.	70763
14	(Number* adj3 (Comprehens* or Knowledge* or System* or Concept* or Operation* or Word*)).ti,ab,id.	10039
15	Numeral*.ti,ab,id.	1335
16	Numeracy.ti,ab,id.	2008
17	Arithmetic*.ti,ab,id.	11643
18	Computation*.ti,ab,id.	37186
19	Subtraction*.ti,ab,id.	2996
20	Multiplication*.ti,ab,id.	2180
21	Division*.ti,ab,id.	26098
22	(Addition or Additions).ti,ab,id.	256086
23	In addition.ti,ab,id.	231177
24	22 not 23	24909
25	Dyscalculia.ti,ab,id.	634

26	1 or 2 or 3 or 4 or 5 or 6 or 7 or 8 or 9 or 10 or 11 or 12 or 13 or 14 or 15 or 16 or 17 or 18 or 19 or 20 or 21 or 24 or 25	195933
27	"Fingers (Anatomy)"/	1553
28	Finger tapping/	869
29	"Hand (Anatomy)"/	3441
30	Gestures/	4856
31	Fine motor skill learning/	314
32	Physical Dexterity/	561
33	Dyspraxia/	978
34	(Finger or Fingers).ti,ab,id.	13473
35	(Hand or Hands).ti,ab,id.	97464
36	Gestur*.ti,ab,id.	11917
37	Fine motor.ti,ab,id.	2844
38	Dexterit*.ti,ab,id.	2315
39	Gnosi*.ti,ab,id.	210
40	Dyspraxia.ti,ab,id.	477
41	Developmental Coordination Disorder*.ti,ab,id.	1203
42	27 or 28 or 29 or 30 or 31 or 32 or 33 or 34 or 35 or 36 or 37 or 38 or 39 or 40 or 41	122147
43	26 and 42	6105
44	Nursery School Students/	534
45	Preschool Students/	11943
46	Kindergarten Students/	5903
47	Primary School Students/	3383
48	Elementary School Students/	41870
49	Intermediate School Students/	112
50	Middle School Students/	9382
51	Junior High School Students/	11659
52	High School Students/	33501
53	Special Education Students/	8144

54	Preschool Education/	4833
55	Elementary Education/	3934
56	Middle School Education/	852
57	Secondary Education/	6870
58	High School Education/	4249
59	Early Childhood Development/	14454
60	Childhood Development/	74246
61	Adolescent Development/	50322
62	((Nursery School* or Preschool* or Kindergarten* or Primary School* or Elementary School* or Intermediate School* or Middle School* or Secondary School* or Junior High School* or High School* or Special Education or Special Need* or Disabilit*) adj3 (Student* or Learner*)).ti,ab,id.	84075
63	((Preschool* or Elementary or Primary or Middle School* or Secondary or High School* or General or Special) adj3 Education).ti,ab,id.	49132
64	Child*.ti,ab,id.	747755
65	Adolescen*.ti,ab,id.	273071
66	Kid*.ti,ab,id.	12063
67	Young*.ti,ab,id.	283335
68	Preteen*.ti,ab,id.	340
69	Teen*.ti,ab,id.	23863
70	Youth*.ti,ab,id.	110939
71	Kindergart*.ti,ab,id.	22133
72	Preschooler*.ti,ab,id.	15920
73	Pre-K.ti,ab,id.	742
74	Pupil*.ti,ab,id.	27790
75	Schooler*.ti,ab,id.	1175

76	44 or 45 or 46 or 47 or 48 or 49 or 50 or 51 or 52 or 53 or 54 or 55 or 56 or 57 or 58 or 59 or 60 or 61 or 62 or 63 or 64 or 65 or 66 or 67 or 68 or 69 or 70 or 71 or 72 or 73 or 74 or 75	1213567
77	43 and 76	1618
78	limit 43 to (160 preschool age <age 2 to 5 yrs> or 180 school age <age 6 to 12 yrs> or 200 adolescence <age 13 to 17 yrs>)	1087
79	77 or 78	1829

Note. Database searches conducted in January 2021 and updated on November 18, 2021.

Part 2: Search strategy - Ovid ERIC (All).

	Search term(s)	Results retrieved
1	Calculus/	3303
2	Algebra/	7886
3	Mathematics/	11875
4	Mathematics Achievement/	15896
5	Mathematics Activities/	2846
6	Mathematics Curriculum/	5981
7	Mathematics Education/	26193
8	Mathematics Instruction/	38818
9	Mathematics Skills/	9023
10	Number Systems/	645
11	Number Concepts/	4614
12	Number Operations/	4079
13	Numbers/	2446
14	Numeracy/	3284
15	Arithmetic/	4079
16	Computation/	8142
17	Mental Computation/	325
18	Subtraction/	1001
19	Multiplication/	1319
20	Division/	535
21	Addition/	1068
22	(Calculus or calculati*).ti,ab.	10128
23	Algebr*.ti,ab.	8275
24	Math*.ti,ab.	100505
25	(Number* adj3 (Comprehens* or Knowledge* or System* or Concept* or Operation* or Word*)).ti,ab.	5536

26	Numeral*.ti,ab.	661
27	Numeracy.ti,ab.	2740
28	Arithmetic*.ti,ab.	5421
29	Computation*.ti,ab.	7644
30	Subtraction*.ti,ab.	1701
31	Multiplication*.ti,ab.	1853
32	Division*.ti,ab.	16783
33	(Addition or Additions).ti,ab.	64454
34	In addition.ti,ab.	58212
35	33 not 34	6242
36	Dyscalculia.ti,ab.	148
37	1 or 2 or 3 or 4 or 5 or 6 or 7 or 8 or 9 or 10 or 11 or 12 or 13 or 14 or 15 or 16 or 17 or 18 or 19 or 20 or 21 or 22 or 23 or 24 or 25 or 26 or 27 or 28 or 29 or 30 or 31 or 32 or 35 or 36	160996
38	Psychomotor Skills/	6075
39	(Finger or fingers).ti,ab.	1664
40	(Hand or hands).ti,ab.	26439
41	Gestur*.ti,ab.	2985
42	Fine motor.ti,ab.	789
43	Dexterit*.ti,ab.	765
44	Gnosi*.ti,ab.	19
45	Dyspraxia.ti,ab.	70
46	Developmental Coordination Disorder*.ti,ab.	183
47	38 or 39 or 40 or 41 or 42 or 43 or 44 or 45 or 46	36639
48	37 and 47	4496
49	Children/	47844
50	Preschool children/	23658
51	Young children/	24298
52	Preadolescents/	3364
53	Early adolescents/	4378

54	Adolescents/	52135
55	Late adolescents/	1349
56	Kindergarten/	12444
57	Elementary School Students/	51190
58	Middle school students/	16835
59	Secondary School Students/	24314
60	Junior high school students/	5890
61	High school students/	39145
62	Students with disabilities/	3326
63	Special needs students/	9571
64	Child Development/	22520
65	Adolescent Development/	4300
66	Early Childhood Education/	32498
67	Preschool Education/	23242
68	Elementary Education/	75862
69	Primary Education/	19137
70	Secondary Education/	91106
71	General Education/	6110
72	Special Education/	23033
73	Child*.ti,ab.	304893
74	Adolescen*.ti,ab.	50350
75	((Nursery School* or Preschool* or Kindergarten* or Primary School* or Elementary School* or Intermediate School* or Middle School* or Secondary School* or Junior High School* or High School* or Special Education or Special Need* or Disabilit*) adj3 (Student* or Learner*)).ti,ab.	79964
76	((Preschool* or Elementary or Primary or Secondary or Middle school* or High school* or General or Special) adj3 Education).ti,ab.	77862
77	Kid*.ti,ab.	7198

78	Young*.ti,ab.	89794
79	Preteen*.ti,ab.	111
80	Teen*.ti,ab.	10651
81	Youth*.ti,ab.	49556
82	Kindergart*.ti,ab.	22487
83	Preschooler*.ti,ab.	7398
84	Pre-K.ti,ab.	1422
85	Pupil*.ti,ab.	28453
86	Schooler*.ti,ab.	838
87	49 or 50 or 51 or 52 or 53 or 54 or 55 or 56 or 57 or 58 or 59 or 60 or 61 or 62 or 63 or 64 or 65 or 66 or 67 or 68 or 69 or 70 or 71 or 72 or 73 or 74 or 75 or 76 or 77 or 78 or 79 or 80 or 81 or 82 or 83 or 84 or 85 or 86	693533
88	37 and 87	75157
89	Elementary school mathematics/	12123
90	Middle School Mathematics/	161
91	Secondary School Mathematics/	11962
92	88 or 89 or 90 or 91	83638
93	92 and 47	2589
94	limit 48 to (early childhood education or elementary education or elementary secondary education or grade 1 or grade 2 or grade 3 or grade 4 or grade 5 or grade 6 or grade 7 or grade 8 or grade 9 or grade 10 or grade 11 or grade 12 or high schools or intermediate grades or junior high schools or kindergarten or middle schools or preschool education or primary education or secondary education)	1447
95	93 or 94	2878

Note. Database searches conducted in January 2021 and updated on November 18, 2021

Table S2. Methods applied in included studies

	Country of origin	Design	Number and Type of participants	Age and/or school level	Conditions	Type of intervention	Finger task	Calculation task
Alloway & Archibald (2008)	UK	Cross-sectional study	DLD, DCD without DLD, DCD (*n*=34)	*M*=8.3 years			Manual Dexterity (MABC)	Numerical Operation (WOND)
Alloway & Temple (2007)	UK	Cross-sectional study	DCD, Unspecified LD (*n*=40)	Primary school (*M*=9.75 years)			Manual Dexterity (MABC)	Numerical Operation (WOND)
Alloway & Warner (2008)	UK	Non-randomized control trial	DCD, DCD-suspect (*n*=20)	*M*=7.3 years		Motor skills training	MABC checklist	Numerical Operation (WOND)

Annett & Manning (1990)	UK	Cross-sectional study	TD (*n*=149)	Primary school (*M*=121 months)			Pegboard + Evaluation of hand preference	Mathematics attainment test (NFER) or Mathematical problem solving (Richmont Tests of Basic Skills)
Asakawa et al. (2014)	Japan	Longitudinal study	TD (*n*=30)	Preschool (followed by 4 to 6 years)			Pegboard test, Rhythmic hand movements	Addition
Asakawa et al. (2019)	Japan	Randomized control trial	TD (*n*=80)	Primary school (G1)		Motor skills training	Pegboard test (SOT-2103)	Arithmetic (WISC-III)

Bahadir (2017)	Turkey	Qualitative design	TD (*n*=11)	Primary school (G2)		Teaching finger-based multiplication strategies		Multiplication
Barnes et al. (2011)	USA	Cohort study	TD, SB (*n*=102)	Followed by 36 to 60 months			Pegboard test	Addition and subtraction
Baroody (1987)	USA	Qualitative design	TD (*n*=17)	Kindergarten			Finger counting	Addition
Benton et al. (1951)	USA	Cross-sectional study	TD, ID (*n*=50)	TD: *M*=11.1 years ID: *M*=16.7 years			Finger gnosia	Arithmetic (Iowa Every Pupil battery)
Berteletti & Booth (2015)	USA	Cross-sectional study	TD (*n*=40)	*M*=11 years			Motor ROI	Subtraction and multiplication
Björklund et al. (2019)	Sweden	Qualitative design	TD (*n*=9)	Preschool			Finger counting	Subtraction

Brooks et al. (2018)	India	Cross-sectional study	Study 1 TD (*n*=226)	*M*=10.8 years			Gesture size + number of moves	Addition
		Cross-sectional study	Study 2 TD (*n*=52)	*M*=11.75 years	Baseline, blindfold, no hand, motor interference		Gestural movements	Addition
Canobi (2004)	UK	Cross-sectional study	TD (*n*=90)	Primary school (G1, G2 and G3)			Finger counting	Addition and subtraction
Carlson et al. (2013)	USA	Cross-sectional study	TD (*n*=97)	*M*=10.59 years			Visuomotor coordination task (DTVMI)	Math subtests (KTEA-II, WIAT-II, WJ-III)
Chao et al. (2000)	USA	Cluster randomized control trial	TD (*n*=166)	Kindergarten	Structured, varied materials	Teaching number concepts with	Finger counting	Addition and subtraction

						physical materials		
Cho & So (2018)	Singapore	Cross-sectional study	TD (*n*=180)	Primary school (*M*=7;1 years)	Physical abacus, hands free mental abacus (MA), hands restricted MA			Addition and subtraction
Costa et al. (2011)	Brazil	Cross-sectional study	TD, MLD (*n*=98)	Primary school (8 to 11 years)			Finger gnosia	Arithmetic (TDE)
Costa-Giomi (2004)	Canada	Non-randomized control trial	TD (*n*=117)	Primary school (G4)		Piano intervention		Mathematical computation (CAT-2)

Crollen & Noël (2015)	Belgium	Cross-sectional study	TD (*n*=49)	Primary school (G1 and G4)	Squeeze ball with hand during calculation, squeeze ball with foot, control			Addition
Dielman & Furuno (1970)	USA	Cross-sectional study	TD (*n*=1012)	N/A			Checklist about FMS completed by teacher	Checklist completed by teacher
Dinehart & Manfra (2013)	USA	Longitudinal study	TD (*n*=3234)	Kindergarten (K) (followed by K to G2)			Fine motor manipulation subtest (LAP-D)	Math subtest (SAT10)

Dupont-Boime & Thevenot (2018)	Switzerland	Cross-sectional study	TD (*n*=86)	kindergarten			Finger counting	Addition
Farrington-Flint et al. (2009)	UK	Cross-sectional study	TD (*n*=50)	Primary school (G1 and G2)			Finger counting	Addition and subtraction
Fuson (1986)	USA	Non-randomized control trial	TD (*n*=110)	Primary school (G1)		Teaching to subtract by counting up		Subtraction
Fuson & Secada (1986)	USA	Non-randomized control trial	TD (*n*=213)	Primary school (G1 and G2)		Teaching to add by counting on		Addition
Fuson & Kwon (1992)	USA	Qualitative design	TD (*n*=36)	Primary school (G1)			Finger counting	Addition and subtraction
Fuson & Willis (1988)	USA	Non-randomized control trial	TD (from "half class" to *n*=45)	Primary school (G1 and G2)		Teaching to subtract by counting up		Addition and subtraction

Geary et al. (1991)	USA	Longitudinal study	TD, MLD (*n*=52)	Primary school (followed by G1 or G2 to one year later)			Finger counting	Addition
Geary et al. (1993)	USA	Cross-sectional study	TD (*n*=51)	Kindergarten			Finger counting	Addition
Geary et al. (2004)	USA	Cross-sectional study	TD, MLD (*n*=149)	Primary school (G1, G3, and G5)			Finger counting	Addition
Gomez et al. (2015)	France	Cross-sectional study	TD, DCD (*n*=40)	Primary school (*M*=8.48 years)			Manual Dexterity (MABC)	Addition

Gracia-Bafalluy & Noël (2008)	Belgium	Non-randomized control trial	TD (*n*=47)	Primary school (G1)		Finger gnosia training	Finger gnosia	Addition
Holsti et al. (2002)	Canada	Cross-sectional study	PB with and without DCD, TD (*n*=91)	9 years			Fine motor index (BOMP)	Arithmetic achievement (WRAT-R)
Ilardi & LaMotte (2021)	USA	Cross-sectional study	CHD with abnormal neurological development (*n*=105)	Primary and secondary school			Pegboard test	Calculation (WIAT-II or WJ-III)
Jordan et al. (1992)	USA	Cross-sectional study	TD (*n*=84)	Kindergarten			Finger counting	Addition and subtraction

Jordan et al. (2003)	USA	Longitudinal study	TD, MLD, DLD, MLD+DLD (*n*=210)	Primary school (followed by G2 to G3)			Finger counting	(a) Exact calculation of arithmetic combinations, (b) story problems, (c) approximate arithmetic, (d) place value, (e) calculation principles, (f) retrieval of number facts, and (g) written computation.

Jordan et al. (2008)	USA	Cohort study	TD (*n*=414)	Kindergarten (followed by K to G2)			Finger counting	Addition
Kiessling et al. (1983)	USA	Cross-sectional study	TD, CP (*n*=29)	7 to 16 years			Pegboard test	Math subtest (WRAT)
Kinsbourne & Warrington (1963)	UK	Cross-sectional study	DLD (*n*=13)	8-14 years + one 31 years-old participant			Finger gnosia	Addition and subtraction
Kohen-Raz & Masalha (1988)	Israel	Cross-sectional study	TD, Df (*n*=60)	Primary school (*M*=8.5 years)	Original Rey, Modified Rey			Addition
Koponen et al. (2007)	Finnish	Case-control study	DLD (*n*=2)	Child A: 10;10 years Child B: 10;5 years		Finger strategy instruction during calculation		Addition

Krinzinger et al. (2011)	Germany	Cross-sectional study	TD (*n*=33)	Primary school (*M*=108 months)			Visual guided finger movement task	Addition
Kullberg & Björklund (2020)	Sweden	Qualitative design	TD (*n*=58)	Preschool			Finger counting	Addition and Subtraction (Word problem)
Lindgren (1978)	USA	Cross-sectional study	TD (*n*=100)	Kindergarten			Finger gnosia	Arithmetic abilities scale (completed by teachers)
Long et al. (2016)	UK	Cross-sectional study	TD (*n*=204)	Primary school (*M*=7.1 years)			Finger gnosia (Noël, 2005)	Addition and subtraction (Test of Basic Arithmetic and Number Skills)

Lucangeli et al. (2003)	Italy	Cross-sectional study	TD (*n*=200)	Primary school (G3, G4 and G5)			Finger counting	Addition and subtraction
Malone et al. (2020)	Australia	Longitudinal study	TD (*n*=569)	Primary school (Followed by G1 to G2)			Finger gnosia (Long et al., 2016)	Addition and subtraction
Michel et al. (2020)	Germany	Longitudinal study	TD (*n*=206)	Primary school (followed by K to G2)			Manual Dexterity (MABC-2)	Addition and subtraction (DIRG)
Newman (2016)	USA	Cross-sectional study	TD (*n*=76)	Older (9-12 years) Younger (5-8 years)			Finger gnosia + Handedness (Edinburgh Handedness Inventory)	Addition

Newman & Soylu (2014)	USA	Cross-sectional study	TD (*n*=69)	*M*=8.65 years			Finger counting	Addition
Noël (2005)	Belgium	Longitudinal study	TD (*n*=45)	Primary school (followed by G1 to G2)			Finger gnosia	Addition
Nwabueze (2001)	Brunei	Qualitative design	TD (*n*=36)	Primary school (G1)			Finger counting	Addition and Subtraction
Ollivier et al. (2020)	France	Non-randomized control trial	TD (*n*=36)	Kindergarten		Explicit teaching of finger use	Finger counting	Addition and subtraction (word problem)
Pieters et al. (2012b)	Belgium	Cross-sectional study	DCD, TD (*n*=173)	Primary school (*M*=105.1 months)			Manual dexterity (MABC-2)	Arithmetic test (KRT-R + TTR)

Pieters et al. (2012a)	Belgium	Cross-sectional study	MLD, TD (*n*=145)	Primary school (G2, G3 and G4)			Manual dexterity (MABC-2)	Arithmetic test (KRT-R + TTR)
Pitchford et al. (2016)	UK	Cross-sectional study	<u>Study 1</u> TD (*n*=62)	Primary school (G1)			Fine motor precision (BOT-2)	Mathematical reasoning (WIAT-II)
			<u>Study 2</u> TD (*n*=34)	Kindergarten			Fine motor precision (BOT-2)	Mathematical reasoning (WIAT-II)
Raghubar et al. (2015)	USA	Cross-sectional study	SB, TD (*n*=165)	*M*=9.86 years			Pegboard test	Math calculation and math fluency (WJ-R) + Exact and approximate arithmetic experimental tasks

Reeve & Humberstone (2011)	Australia	Cross-sectional study	TD (*n*=65)	Primary school (K and G1)			Finger gnosia + Handedness + Finger counting	Addition
Reynvoet et al. (2020)	Belgium	Cross-sectional study	DCD, TD (*n*=128)	Secondary school (G3 and G4)			DCD diagnosis in line with DMS-V criteria	Arithmetic verification task: subtraction and multiplication
Roberts et al. (2011)	Australia	Cross-sectional study	PB with and without DCD, TD (*n*=132)	8 years			Manual Dexterity (MABC) + CHQ PF50	Arithmetic (WRAT-3)
Saunders et al. (2018)	USA	Case-control study	Moderate ID with (*n*=2) or without	Brad: 13 years Heather: 14 years		Solve video simulation real-word mathematical		Addition and subtraction (Word problems)

			(n=1) Down Syndrome	Benito: 13 years		problems by finger counting using video prompting (VP)		
Siegel (1992)	Canada	Cohort study	PB, TD (n=156)	8 years (followed by 4 months to 8 years)			Manipulation and Eye-Hand coordination subtests (Bayley MDI)	Arithmetic (WRAT)
Strauss & Werner (1938)	USA	Case report	<u>Study 1:</u> Participant with physical and neurological abnormalities (n=1)	15.4 years			Finger gnosia + close eyes and make a fist	Arithmetic achievement

		Cross-sectional study	Study 2: MLD (*n*=40)	N/A			Finger gnosia	Arithmetic achievement
Stegemann & Grünke (2014)	Canada	Non-randomized control trial	TD (*n*=75)	Primary school (G2 and G5)		Chisanbop program		Computation (TOMA)
Svenson et Sjöberg (1982)	Sweden	Longitudinal study	TD (*n*=16)	Primary school (followed by G1 to G3)			Finger counting	Subtraction
Thevenot et al. (2014)	Switzerland	Cross-sectional study	CP, TD (*n*=30)	Primary school (G2 to G6)			CP diagnosis made by a physician	Addition and subtraction
Van Rooijen et al. (2012)	Netherlands	Cross-sectional study	CP (*n*=116)	*M*=7.3 years			Abilhand questionnaire	Arithmetic (Student Monitoring

							completed by parents.	System for Arithmetic Performance)
Van Rooijen et al. (2015)	Netherlands	Cohort study	CP (*n*=56)	Primary school (followed by 6 to 8 years)			Box and Block task	Addition and subtraction
Waber et al. (2000)	USA	Cross-sectional study	Unspecified LD, TD (*n*=343)	7 to 11;11 years			Motor timing control (MTC)	Numerical Operation (WIAT)
Wasner et al. (2016)	Germany	Cross-sectional study	TD (*n*=321)	Primary school (G1)			Finger Gnosia	Addition and subtraction
Werner & Carrison (1942)	USA	Cross-sectional study	ID (*n*=80)	N/A			Finger gnosia	Arithmetic achievement

Wylie et al. (2012)	UK	Longitudinal study	TD, DLD, MLD, DLD+MLD (*n*=85)	Followed by 5 to 7 years			Finger counting	Addition and subtraction
Zafranas (2004)	Turkey	Non-randomized control trial	TD (*n*=61)	5-6 years		Piano/keyboard training	Hand movements (KABC)	Arithmetic subtest (KABC)

Note. TD, Typically Developing; aTD, Atypically Developing; SB, Spina Bifida; DCD, Developmental Coordination Disorders; CP, Cerebral Palsy; DLD, Developmental Language Disorders; Unspecified LD, Unspecified Learning Disorders; MLD, Mathematical Learning Disabilities; CHD, Congenital Heart Disease; Df, Deafness; PNA, Physical and Neurological Abnormalities; K, Kindergarten; G, Grade.

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Table S3. Main results of included studies

	Significance (s or ns)	**Effect size**	**Main finding**
Mathematical education			
Finger strategies			
Baroody (1987)	Descriptive analyses		Kindergartners use different finger counting strategies to solve addition problems. Over the course of development, many children persisted in counting all objects.
Björklund et al. (2019)	Descriptive analyses		Results showed three different ways to use finger strategies during calculation. Children use finger counting strategies with much more complexity than has been suggested in previous studies.
Brooks et al. (2018)	Part 1: s		Mental abacus experts used specific gestures to solve arithmetic problems.
	Part 2: s		In mental abacus, cognitive and premotor processes involved in planning gestural movements play an important role.
Fuson & Kwon (1992)	Descriptive analyses		Two finger methods that allowed fingers to be reused for sums greater than 10 were demonstrated in Korean children. The three composition methods

			structured around 10 observed in children were supported by the two previous methods and by the regularity of the Korean number words following 10 ("ten, ten one, ten two… ten eight").
Kullberg & Björklund (2020)	Descriptive analyses		Results suggest that children need to discern three different aspects to solve computation tasks using finger pattern: "what constitutes the whole, the parts within the whole, and finger patterns as a representation of the cardinality of a set."
Nwabueze (2001)	Descriptive analyses		This study illustrates three different finger counting sequences observed in Bruneian children.
Efficiency of finger strategies			
Bahadir (2017)	descriptive analyses		After being trained to solve multiplication problems with finger strategies, student were more efficient and their motivation was higher.
Chao et al. (2000)	Quantitative analyses done but no quantitative results reported		Finger users were faster at solving problems after being trained with structured materials in which numbers were represented with tile patterns. They were more accurate after training with varied materials in which numbers were represented by pictures of concrete objects.

Cho & So (2018)	s	Range η^2p: 0.06–0.73	The results showed that the participant's level of learning and the complexity of the arithmetic problem influenced the children's performance.
Crollen & Noël (2015)	s	Range η^2: 0.11–0.27	When solving difficult problems, children were less efficient when they had to squeeze a ball with their hand than with their foot. These results suggested that fingers influence children's arithmetic performance.
Dupont-Boime & Thevenot (2018)	s	Range *r*: 0.48–0.57	Results showed that, the more children used finger strategies, the more efficient they were when solving computational problems. When they had to solve addition problems, children with high working memory used more elaborate finger strategies than children with low working memory.
Farrington-Flint et al. (2009)	Quantitative analyses done but no quantitative results reported		When solving addition and subtraction problems, the finger users had a high success rate. Finger users were more accurate at addition than subtraction. The second-graders were more efficient than the first-graders.
Fuson (1986)	s		After being trained to solve subtraction with explicit counting-up finger strategies, the children were more accurate at solving difficult subtraction problems during a timed test. This effect was still observable one month later.

Fuson & Secada (1986)	s		Counting-on with finger counting strategies was efficient, in children, for adding single- and multi-digit numbers.
Fuson & Willis (1988)	s		Children improved their performance on take-away, compare, and equalize word problems after being trained to subtract by counting up with finger counting strategies. A three-year accelerations in learning of subtraction was also shown after training.
Geary et al. (2004)	s		Children with MLD used fingers strategies more often and were less efficient than their TD peers. In first-graders, these observations seem to be associated with a deficit in working memory capacity in children with MLD.
Jordan et al. (1992)	s		Middle-income children used finger counting strategies more often and were more efficient when they solved verbal problems than low-income children, even when the use of finger counting was adjusted.
Jordan et al. (2008)	s	Range *r*: 0.15–0.60	Across development, finger counting and arithmetic performance were less correlated. Boys used finger strategies less often and were more efficient than girls. While low-income children used finger counting regularly over time, middle-income children used these strategies less often after the second grade.

Lucangeli et al. (2003)	Quantitative analyses done but no quantitative results reported		In mental calculation, participants were more efficient when they solved problems using counting on fingers, counting on mental strategies or complex strategies such as that of 1010.
Newman & Soylu (2014)	s		The difference in performance observed between left- and right- starters had an influence on arithmetic skills. This result suggests that there is a link between fingers and numbers.
Ollivier et al. (2020)	s		After being trained to solve computational problems with explicit finger strategies, kindergarten students in the intervention group performed better than those in the control group.
Saunders et al. (2018)	Descriptive analyses		After being trained to solve problems using finger strategies, the three participants' arithmetic performance increased. These results suggest that training based on video prompting combined with systematic instruction was effective in improving participants' computational performance.
Stegemann & Grünke (2014)	ns		After being trained in the Chisanbop finger method, the at-risk fifth graders in the control group had further improved their computing performance compared to those in the experimental group.

From fingers to memory retrieval			
Geary et al. (1991)	TD: s MLD: ns		Over their development, TD children shifted from counting to memory retrieval and were more efficient at retrieval when they solved addition problems. Children with MLD did not shift.
Geary et al. (1993)	s	Range φ: 0.48–0.53	When solving addition problems, Chinese children used more mature strategies than their American peers. Chinese children tended to count verbally when they could not retrieve addition facts. American children, on the other hand, tended to guess at results or count with finger strategies.
Jordan et al. (2003)	Quantitative analyses done but no quantitative results reported		Children with MLD used finger counting more often and more accurately than children with MLD+DLD. These children seemed to have more difficulty than their peers in switching from fingers to memory-based strategies.
Koponen et al. (2007)	Child A: ns Child B: s		After training, Child B switched from finger counting strategies to fact retrieval, unlike Child A. The benefit of this intervention depended on the child's language skills.
Svenson et Sjöberg (1982)	Descriptive analyses		During calculation, switching strategies depended on the level of elaboration of children's memory representations.

Wylie et al. (2012)	s	η^2p= 0.10	Children with MLD and DLD+MLD used finger counting more often than TD and DLD children at Times 3 and 4. Across the four time points, they used memory retrieval consistently for one-fifth of the computational problems.
Cognitive psychology and neuroscience			
Fine motor skills			
Annett & Manning (1990)	s		Results showed that left hand dexterity and arithmetic skills were positively related.
Asakawa et al. (2014)	s		Finger dexterity was a significant predictor of children's arithmetic skills, unlike vocabulary skills.
Asakawa et al. (2019)	s	Range η^2p: 0.07–0.40	After training, a moderate to large improvement in FMS and arithmetic skills was found in children. These results suggest that FMS significantly influence arithmetic abilities.
Alloway & Warner (2008)	ns		In children in intervention group, results showed a significant improvement in motor skills and visuospatial working memory without transfer to academic achievement.

Barnes et al. (2011)	s	Range ΔR^2: 0.10–0.12	Models combining 36-month mathematical ability and language-based, visuospatial, and fine motor abilities at 60 months accounted for considerable variance on 60-month informal mathematical outcomes.
Carlson et al. (2013)	ns		Results suggested that, after controlling SES, gender and IQ, visuomotor coordination seems not influence children's achievement, unlike visuospatial integration skills.
Costa-Giomi (2004)	ns		After piano lessons, there was no improvement in mathematical skills for either the experimental or the control group of children. Only the children's self-esteem improved.
Dielman & Furuno (1970)	s	Range r: 0.13–0.20 $R^2 = .46$	FMS did not make a unique contribution to arithmetic skills when SES and other overall cognitive scores were considered.
Dinehart & Manfra (2013)	s	d=0.09	Among second-graders, object manipulation skills significantly influenced their mathematical abilities.
Holsti et al. (2002)	s		Preterm children with DCD were more likely to have mathematical difficulties than their peers who did not have DCD.
Ilardi & LaMotte (2021)	ns		By a hierarchical linear regression, a significant variance in computational skills was explained by perceptual reasoning, processing speed, and working memory.

Jenks et al. (2009)	s	Range R^2: 0.26–0.35	By the end of the second grade, children with CP enrolled in special education seemed not to have automated simple arithmetic facts, unlike their peers enrolled in regular education. This difference was explained by nonverbal intelligence, left-hand impairment, and epilepsy.
Kiessling et al. (1983)	s (left hand) ns (right hand)	$r = 0.67$	In both CP groups, left hand impairment appeared to be related to the children's arithmetic skills.
Michel et al. (2020)	ns		Without taking into account the executive functions, FMS explained only 3% of the variance in the children's computation abilities. No influence of FMS emerged when executive functions were added to the model.
Pieters et al. (2012a)	s	Range η^2p: 0.22–0.31	Compared with TD children, participants with MLD had mild to severe developmental delays in visual perception, motor coordination and visual-motor integration.
Pieters et al. (2012b)	s	Range η^2p: 0.09–0.34	A difference could be noted between mild and severe DCD children in procedural calculation and fact retrieval. A delay of one year for fact retrieval was found in mild DCD and two years in severe DCD.
Pitchford et al. (2016)	Part 1: s	<u>*r* FMP x math</u>: 0.60 <u>R^2 of full</u>	Arithmetic skills were predicted by fine motor integration and fine motor precision. When word reading was included in the model, the contribution of fine motor integration was not significant.

		model: 0.57	
	Part 2: ns		Only fine motor integration was significantly related to arithmetic skills.
Raghubar et al. (2015)	s	Range adjusted *R2*: 0.18–0.48	Results of mediation models suggested that FMS and verbal working memory mediated the relation of group to approximate arithmetic and that FMS and visual-spatial working memory mediated the relation of group to math fluency.
Siegel (1992)	s	Range *r*: 0.28–0.48	Eye-hand coordination assessed at 12, 18 and 24 months and manipulation scales performed at 4 and 12 months were the best predictors of arithmetic skills in 8-year-old children.
Van Rooijen et al. (2012)	s		The combined model showed that FMS and word decoding were the best predictors of children's arithmetic skills.
Van Rooijen et al. (2015)	s	Full model: 65% of variance	One year after the first assessment, working memory, counting and FMS were related to early arithmetic skills. Working memory and FMS were good predictors of early arithmetic development.

Zafranas (2004)	s		Following piano lessons, children improved significantly in hand movements, gestalt closure, triangles, spatial memory, and arithmetic abilities.
Finger gnosia			
Benton et al. (1951)	Descriptive analyses		No link between finger gnosia and arithmetic skills was shown.
Costa et al. (2011)	s	Range r: 0.30–0.40	Results showed a joint deficit affecting finger gnosia and arithmetic skills independently of working memory abilities. These difficulties seem to be more related to an inability to use fingers to represent the cardinal of a set, point to an object during counting, or reduce cognitive load during calculation.
Gracia-Bafalluy & Noël (2008)	s		After training, an improvement in finger gnosia and arithmetic skills was found in children. These results suggest that finger gnosia promotes the development of arithmetic skills.
Kinsbourne & Warrington (1963)	Descriptive analyses		A joint deficit affecting finger gnosia and arithmetic skills was found in group 2 (profile: verbal IQ > performance IQ), but not group 1 (profile: performance IQ > verbal IQ).
Lindgren (1978)	s	$r = 0.47$	Finger gnosia predicts arithmetic skills and reading achievement and does not appear to be a specific cognitive ability.

Long et al. (2016)	ns		No relationship between finger gnosia and arithmetic skills was found after controlling for age effects.
Malone et al. (2020)	ns		The statistical model showed that only number knowledge and numerosity discrimination, unlike finger gnosia, are unique predictors of arithmetic skills in the early years of schooling.
Newman (2016)	Younger: ns Older: s	$r = 0.32$	The results showed that finger gnosia does not predict arithmetic skills in young children but has a moderate impact in older children.
Noël (2005)	s	range R^2: 0.12–0.14	Finger gnosia was found to have predictive power for arithmetic skills but not on reading skills, proving the specificity of this predictor.
Strauss & Werner (1938)	Part 1: Descriptive analyses		Results suggested that there was no unique relationship between finger gnosia and arithmetic skills.
	Part 2: Descriptive analyses		A joint deficit affecting finger gnosia and arithmetic skills was shown, suggesting a relationship between these two impairments in this case.
Wasner et al. (2016)	s	ΔR^2: 0.16 (add) and 0.17 (sub)	Finger gnosia predicted a unique but small part of the variance in arithmetic performance as compared with effects of general cognitive abilities and early numerical skills.

Werner & Carrison (1942)	Descriptive analyses		A relationship between finger gnosia and arithmetic skills was found even when age and reading abilities were taken into account.
Finger tapping			
Waber et al. (2000)	s		Finger tapping predicted reading and spelling but also arithmetic skills. A finger tapping deficit in children with reading disabilities did not impact their arithmetic skills.
Suppression of synkinetic movements			
Kohen-Raz & Masalha (1988)	s	range *r*: 0.18–0.54	The influence of the suppression of synkinetic movements on deaf students' difficulties in mastering arithmetic skills was demonstrated.
Hand preference			
Annett & Manning (1990)	s		The analyses showed a greater proportion of non-right-handers among children who performed well in computation.
Newman (2016)	ns		No influence of hand preference was found on arithmetic skills.
Rhythmic hand movements			
Asakawa et al. (2014)	ns		No link between rhythmic hand movements and calculation was found.
Brain correlates			

Berteletti & Booth (2015)	Quantitative analyses done but no quantitative results reported		Motor area activations were found in children aged from 8 to 13 years old only when they solved subtraction problems.
Krinzinger et al. (2011)	Quantitative analyses done but no quantitative results reported		Activations related to non-symbolic exact addition were found. Activations were more significant for calculation than for magnitude comparison. Furthermore, they were stronger in non-symbolic than in symbolic addition.
Motor disorders			
Alloway & Archibald (2008)	ns		These results indicate that, although the two groups differed in language skills, they performed at similar levels in arithmetic skills.
Alloway & Temple (2007)	ns		Children with DCD had similar arithmetic performance to children with Unspecified LD.
Gomez et al. (2015)	s (RT) ns (accuracy)		Results showed that children with DCD were slower than but as accurate as TD children when solving addition problems.
Reynvoet et al. (2020)	ns		Children with DCD and control children performed similarly on arithmetic tests.

Roberts et al. (2011)	s		Preterm children with DCD had more difficulties with calculation than those without DCD.
Thevenot et al. (2014)	ns		Results suggested that the arithmetic skills of children with hemiplegia were preserved. Children probably compensated for their difficulties with adaptive strategies such as memory-based strategies.
Study combining mathematical education and cognitive psychology/neuroscience methods			
Reeve & Humberstone (2011)	s	$\eta^2 = 0.95$	Results demonstrated a strong relationship between finger gnosia subgroup and success in solving single-digit addition among finger users. The findings showed that the finger gnosia and computational finger use subgroups were systematically associated.

Note. s, significant; ns, non-significant.

Annexe 2 : matériel supplémentaire de la discussion générale

Table 1: Synthèses des études consultées traitant des habiletés motrices fines

Références	Terminologie	Définition	Composante évaluée	Tâche
Annett and Manning (1990)	Habileté manuelle		Manipulation d'objets	Pegboard
Asakawa and Sugimura (2014)	Dextérité	Motricité fine au niveau des doigts.	Manipulation d'objets	Pegboard
			Mobilisation de la main	Mouvements rythmiques
Asakawa et al. (2017)	HMF	Mouvements des doigts	Manipulation d'objets	Pegboard
Asakawa and Sugimura (2022)	HMF	Contrôle et coordination de la musculature distale des mains et des doigts	Manipulation d'objets	Pegboard
Ashkenazi et al. (2022)	HMF		Manipulation d'objets, habiletés grapho-motrices	Questionnaire hétéro rapporté (parents)

Barnes et al. (2011)	HMF		Manipulation d'objets	Pegboard
Cameron et al. (2012)	HMF		Manipulation d'objets, habiletés grapho-motrices	ESI-R Ex : Construire un pont, copier des figures
Carlson et al. (2013)	Deux sous-composantes dans les HMF :			
	(1) Coordination visuo-motrice	Consiste à contrôler les petits mouvements des doigts.	Manipulation d'objets	Tracer un chemin entre deux lignes
	(2) Intégration visuo-spatiale	Consiste à créer une représentation mentale d'une image et à la reproduire à l'aide de petits mouvements musculaires contrôlés.	Habiletés grapho-motrices	Copie de figures
Dielman and Furuno (1970)	Coordination motrice fine		Manipulation d'objets, habiletés	Questionnaire hétéro rapporté (enseignants

			grapho-motrices	
Dinehart and Manfra (2013)	Deux sous-composantes dans les HMF :			
	(1) manipulation d'objets	Exige des enfants qu'ils fassent preuve de dextérité manuelle en manipulant des objets	Manipulation d'objets	LAP-D Ex : Enfiler des perles, pegboard
	(2) Ecriture motrice fine	Compétence grapho-motrices	Habiletés grapho-motrices	LAP-D Copies figures
Escolano-Perez et al. (2020)	Deux sous-composantes dans les HMF :	HMF = Implique l'action de petits groupes de muscles		
	(1) Coordination motrice fine	Mouvements de petits muscles sans intégration d'informations visuo-spatiale	Manipulation d'objets, mobilisation de la main	Faire des nœuds autour d'un stylo Toucher chaque doigt avec le pouce.
	(2) L'intégration motrice fine	Organisation des petits muscles de la main et des	Habiletés grapho-motrices	Copie de lettre, de mots et de nombres

		doigts à travers le traitement de stimuli visuels.		
Fischer et al. (2018)	HMF	Mouvements de petits muscles qui nécessite la coordination entre l'œil et la main	Manipulation d'objets	Pegboard Enfiler des perles Retourner des tiges en bois
Fischer et al. (2020)	Deux sous-composantes dans les HMF :	HMF = Mouvements de petits muscles qui nécessite la coordination entre l'œil et la main.		
	(1) Dextérité		Manipulation d'objets	MABC-2 Poster les jetons, enfiler les perles
	(2) compétences grapho-motrices		Habiletés grapho-motrices	Tracer un chemin entre deux lignes
Fischer et al. (2022)	Deux sous-composantes dans les HMF :	HMF = Habileté à bouger les doigts individuellement et à traiter des tâches visuo-motrices.		

	(1) Dextérité		Manipulation d'objets	MABC-2 Poster les jetons, enfiler les perles Tracer un chemin entre deux lignes
	(2) Agilité des doigts	Habileté à bouger séparément chaque doigt	Mobilisation de la main	Lever un ou deux doigts.
Gashaj et al. (2019)	HMF		Manipulation d'objets	MABC-2 Poster les jetons, enfiler les perles Tracer un chemin entre deux lignes
Ilardi and LaMotte (2021)	Dextérité		Manipulation d'objets	Pegboard
Khng and Ng (2021)	HMF	Habileté à contrôler et coordonner ses mains dans la manipulation d'objets ou d'outils.	Manipulation d'objets, habiletés grapho-motrices	IED-III Ex : Construire une tour, dessiner, écrire

Kim et al. (2017)	Deux sous-composantes dans les HMF :			
	(1) Coordination motrice fine	Englobe les mouvements musculaires, y compris la coordination, la dextérité des doigts, les séquences motrices, la vitesse et la précision du geste.		Beery VMI Tracer un chemin entre deux lignes
	(2) Intégration visuo-motrice	Concept complexe qui repose l'intégration de l'attention et de la coordination motrice fine.	Habiletés grapho-motrices	Beery VMI Copies de figures
Michel et al. (2020)	HMF		Manipulation d'objets	MABC-2
Orrantia et al. (2022)	HMF		Mobilisation de la main	NEPSY-2 Imitation de configurations de doigts

Pagani et al. (2010)	HMF		Manipulation d'objets	Tenir un stylo, manipulation d'objets
Penner-Wilger et al. (2007)	HMF		Mobilisation de la main	Finger tapping
Pieters et al. (2012a) Desoete, Roeyers	Deux sous-composantes dans les HMF :			
	(1) Dextérité		Manipulation d'objets	MABC-2
	(2) Coordination motrice fine		Habiletés grapho-motrices	Beery VMI Copies de figures
Pieters et al. (2012b)	Deux sous-composantes dans les HMF :			
	(1) Dextérité		Manipulation d'objets	MABC-2
	(2) Ecriture		Habiletés grapho-motrices	SOS

Pieters et al. (2015)	Trois sous-composantes dans les HMF :			
	(1) Dextérité		Manipulation d'objets	MABC-2
	(2) Intégration visuo-motrice		Habiletés grapho-motrices	Beery VMI Copies de figures
	(3) Ecriture		Habiletés grapho-motrices	SOS
Pitchford et al. (2016)	Deux sous-composantes dans les HMF :	HMF = Compétences qui englobe le contrôle et la coordination de la musculature distale des mains et des doigts.		
	(1) Précision motrice fine	Habileté manuelle fine "pure" qui repose sur une composante visuelle-perceptuelle minimale.	Manipulation d'objets	BOT-2 Ex : Couper avec des ciseaux Plier une feuille

	(2) Intégration visuo-motrice	Aptitude manuelle nécessitant des mouvements synchronisés main-œil et le traitement d'un stimulus visuel afin de produire un résultat moteur adéquat.	Habiletés grapho-motrices	BOT-2 Ex : Copie de figures
Raghubar et al. (2015)	HMF		Manipulation d'objets	Pegboard
Siegel (1992)	Compétences motrices perceptuelles		Habiletés grapho-motrices	Beery VMI Copie de figures
Son and Meissels (2006)	Habiletés visuelles motrices		Manipulation d'objets, habiletés grapho-motrices	ESI-R Ex : Construire un pont, copier des figures
Suggate et al. (2017)	HMF		Manipulation d'objets	Ex : Pegboard, Enfiler les perles

Van Rooijen et al. (2012)	HMF		Manipulation d'objets, habiletés grapho-motrices	Questionnaire hétéro rapporté (parents)
Van Rooijen et al. (2015)	HMF		Manipulation d'objets	Manipulation blocks en bois
Zafranas (2004)	Mouvement de la main		Mobilisation de la main	Séquence de tapotements sur la table (main)

Table 2: Synthèse des études actuelles traitant des gnosies digitales

Références	Terminologies	Définition	Tâche	Indices psychométriques
Asakawa and Sugimura (2022)	Gnosies digitales	Habileté à percevoir et discriminer ses propres doigts	(1) touche 1 doigt avec la main cachée (10 essais) (2) touche 2 doigts simultanément avec la main cachée (10 essais) Nommer le(s) doigt(s) touchés sur un dessin.	
Costa et al. (2011)	Gnosies digitales	Habiletés à discriminer les doigts	(1) touche 1 doigt avec la main visible (4 essais) (2) touche 1 doigt avec la main cachée (8 essais) (3) touche 2 doigts simultanément avec la main visible (12 essais) Montre le(s) doigt(s) touché(s) avec l'index de l'autre main OU nomme les doigt(s) touché(s) sur un dessin	Consistance interne : KR-20=0.79 (acceptable)

Gracia-Bafalluy and Noël (2008)	Gnosies digitales	Habileté à différencier ces propres doigts quand ils sont touchés sans indice visuel	(1) touche 1 doigt avec la main cachée (10 essais) (2) touche 2 doigts simultanément avec la main cachée (5 essais) (3) touche 2 doigts séquentiellement avec la main cachée (5 essais) Montre le doigt touché avec son index de l'autre main.	
Fayol et al. (1998)	Gnosies digitales	Habileté à identifier et organiser des afférents	Touche 5 doigts séquentiellement avec les yeux fermés. Doigt numéroté de 1 à 5, rappel de la séquence.	
	Discrimination des doigts		Touche 2 doigts simultanément avec les yeux fermés (4 essais). Montre les doigts touchés avec l'index de l'autre main.	

Fischer et al. (2022)	Gnosies digitales	Conscience de sa propre main	Touche 1 doigt avec la main cachée (7 essais). Expérimentateur montre un doigt sur une figure, enfant indique s'il s'agit du doigt touché ou pas	Consistance interne : α=.39 (non acceptable)
Long et al. 2016	Gnosies digitales	Conscience des doigts Habileté à identifier les doigts	(1) Touche 1 doigt avec la main cachée (5 essais). (2) Touche 2 doigts simultanément avec la main cachée (10 essais) (3) Touche 2 doigts séquentiellement avec la main cachée (10 essais) Montre le(s) doigt(s) touché(s) avec l'index de l'autre main.	
Malone et al. (2020)	Gnosies digitales	Habileté à différencier des doigts	(1) Touche 1 doigt avec la main cachée (5 essais).	

		sans indice visuel	(2) Touche 2 doigts simultanément avec la main cachée (10 essais) (3) Touche 2 doigts séquentiellement avec la main cachée (10 essais) Montre le(s) doigt(s) touché(s) avec l'index de l'autre main.	
Newman (2016)	Gnosies digitales		(1) Touche 1 doigt avec la main cachée (5 essais). (2) Touche 2 doigts séquentiellement avec la main cachée (5 essais). Montre le(s) doigt(s) touché(s) avec l'index de l'autre main.	
Noël (2005)	Gnosies digitales	Habileté à reconnaitre et discriminer ses doigts	(1) Touche 1 doigt avec la main cachée (10 essais).	Fidélité test-retest : r=.50 (faible)

			(2) Touche 2 doigts simultanément avec la main cachée (5 essais). (3) Touche 2 doigts séquentiellement avec la main cachée (5 essais). Montre le(s) doigt(s) touché(s) avec l'index de l'autre main.	
Penner-Wilger et al.2007	Gnosies digitales	Habileté à se représenter mentalement ses doigts	Touche 2 doigts avec la main cachée (10 essais pour chaque main). Montre les doigts touchés avec l'index de l'autre main.	
Reeve and Humberstone (2011)	Gnosies digitales	Habileté à distinguer ses doigts	Touche 1 doigt avec la main cachée. Implique uniquement le pouce, l'annulaire et l'index.	

			Expérimentateur montre un doigt sur une figure, enfant indique s'il s'agit du doigt touché ou pas. 72 essais	
Van Rinsveld et al. (2020)	Gnosies digitales	Habileté à distinguer ses propres doigts	(1) Touche 1 doigt avec la main cachée (10 essais). (2) Touche 2 doigts simultanément avec la main cachée (5 essais) (3) Touche 2 doigts séquentiellement avec la main cachée (5 essais) Montre le(s) doigt(s) touché(s) avec l'index de l'autre main.	
Wasner et al. 2016	Gnosies digitales	Habileté à discriminer les doigts sans feedback visuel	Tâche 1 : (1) Touche 1 doigt avec la main cachée (3 essais). (2) Touche 2 doigts	Consistance interne : α=.55 (questionnable)

			séquentiellement avec la main cachée (5 essais Montre le(s) doigt(s) touché(s) avec l'index de l'autre main. Tâche 2 : (1) Touche 1 doigt avec la main cachée (4 essais). (2) Touche 2 doigts séquentiellement avec la main cachée (4 essais) Expérimentateur montre un doigt sur une figure, enfant indique s'il s'agit du doigt touché ou pas	

Résumé

Alors que l'utilisation des doigts par les enfants fait encore l'objet de débats chez les enseignants et les scientifiques, la présente thèse a été conduite afin de mieux comprendre *la contribution des doigts dans le développement des compétences numériques et arithmétiques typique et atypique*. L'étude des habiletés sensori-motrices (gnosies digitales et habiletés motrices fines (HMF)) était au cœur de ce projet de thèse. Après avoir examiné la littérature à travers deux revues narratives et une revue méthodique, quatre recherches expérimentales ont été conduites. Les deux premiers travaux, menés chez des enfants tout-venant âgés de 3 à 8 ans, visaient *à clarifier le rôle des habiletés sensorimotrices dans le développement des compétences arithmétiques ainsi que les processus sous-jacents à ces relations.* Entre 3 et 5 ans, nos recherches ont montré que les HMF étaient un meilleur prédicteur des habiletés arithmétiques que les gnosies digitales. Par ailleurs, les HMF sont liées aux compétences arithmétiques par la maitrise des concepts cardinaux. A partir de 6 ans, ce pattern de résultats change puisque que seules les gnosies digitales apparaissent comme étant un prédicteur significatif du développement arithmétique. Cette relation n'est pas médiée par l'utilisation du comptage sur les doigts. Conduites auprès d'enfants présentant un déficit moteur (TDC et IMC), les deux dernières recherches *visaient à explorer les conséquences de ces altérations motrices sur les traitements numériques et à proposer des pistes d'intervention*. Alors qu'ils présentent des HMF déficitaires, les enfants TDC produisent des gestes de comptage semblables à ceux d'enfants tout-venant. Ils sont davantage limités par leurs ressources en mémoire de travail que par leur déficit moteur pour traiter des tâches ordinales sollicitant fortement la mémoire de travail. Ce n'est que quand le déficit moteur est très important, que le recours aux supports externes (doigts et matériel de manipulation) semble fortement affecté. C'est le cas chez NG, un enfant IMC dont le handicap moteur empêche l'utilisation de ces supports pour soulager sa mémoire de travail déficitaire, lors des traitements arithmétiques. Une rééducation du calcul, ancrée dans l'Evidence Based Practice (EBP) et conçue à partir d'un matériel adapté a été conduite avec succès auprès de cet enfant. La présente thèse ouvre de nombreuses perspectives pour la conduite de futures recherches à visée tant fondamentale que clinique.