Advances in the study of handwritten letters:

Influential factors, measures and methods

by

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“[L]etter formation should not be seen as biophysical processes only. Indeed, cognitive variables such as linguistic and lexical complexity, word and letter length, and other contextual factors significantly interfered in real-time production.”

(van Galen, 1991: 186)

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It took six years to complete this thesis. I started this PhD journey in 2018 with no skills in R and with a very limited understanding of cognitive psychology in general. But they say (or do they?) that a PhD is for learning. I did learn. It was painful, rewarding, frustrating and fun. It resulted in this thesis. I went to schools, collected data, processed data, analysed data, read literature, presented at conferences, wrote, rewrote, rewrote, rewrote, rewrote and then rewrote some more. But I had help every step of the way and for that I am forever grateful.

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Summary

This thesis is an in-depth exploration of factors that influence pen-movement fluency when beginning writers form single letters by hand. More specifically, the aim is to explore how factors within the letter, the child and the word affect pen-movement fluency when children in first grade write single letters by hand.

Assessment of children's handwriting mainly focuses on legibility and neatness and less on the production process. In other areas of handwriting research, the focus has shifted from product to process. Process data from letter formation is collected with a digital drawing tablet, and specialised software captures how the pen moves on and above the tablet. Measurements of pen-movement fluency are calculated based in these data. However, such a fluency measure requires that we first identify segments that are capable of being compared directly.

In the first study we explore how pen-movement fluency measures can be used to assess letter formation in beginning writers. We discuss letter characteristics that may affect fluency and challenges associated with letters formed by beginning writers. In response to these discussions, we demonstrate that all letters can be segmented into straight and curved features. We also propose how to assess whether features are produced with sufficient accuracy. We illustrate how letter features can be analysed across letters and children. We find that the children produced letter features less fluently and less accurately than the adults, and that the inaccurate features were produced more slowly and less fluently than the accurate ones.

In the second study we explore how children's pen control and letter knowledge influence pen-movement fluency. It is well established in literature that children's letter formation ability is associated with fine motor skills and letter knowledge. We discuss the complexity in the skills needed for fluent letter formation. We find that ability to copy

letters and letter-like symbols is associated with letter knowledge and complex pen control tasks. Hence motor execution in letter formation is influenced by higher level processing, such as the retrieval of a motor plan for an allograph.

In the third study we explore how word characteristics affect fluency of letter production in the word-initial letter. Again, it is well established in literature that word length and word frequency affect written production. Long words and low frequency words are more prone to spelling errors and short words and high frequency words are associated with faster response times. We discuss how these factors may affect the letter formation process in beginning writers. We find that there is no difference in reaction time when children write words to dictation, or in pen-movement fluency in the word initial letter. But, in line with previous research, we find that low frequency and long words are more prone to spelling errors.

To conclude, this study demonstrates that it is possible to assess pen-movement fluency in children's letter formation. Future research should pay attention to pen-movement fluency when seeking to understand the complex cascade of processes of letter formation that must be combined in order to produce text fluently.

Oppsummering

Denne avhandlingen er et dyp-dykk i de faktorer som påvirker flyt i pennebevegelsen når begynnende skrivere former enkeltbokstaver for hånd. Mer spesifikt er målet å utforske hvordan faktorer innenfor bokstaven, barnet og ordet påvirker flyten i pennebevegelsen når barn i første klasse former bokstaver for hånd.

Vurdering av barns håndskrift fokuserer hovedsakelig på lesbarhet og penhet. Det er mindre fokus på produksjonsprosessen. På andre områder innen håndskriftforskning har fokus skiftet fra produkt til prosess. Prosessdata fra bokstavforming samles inn med et digitalt tegnebrett, og spesialisert programvare fanger opp hvordan pennen beveger seg på og over nettbrettet. Disse dataene kan deretter konverteres til mål på flyt i pennebevegelsen. Men, slike flytmål forutsetter at vi først identifiserer segmenter som kan sammenlignes direkte.

I den første studien utforsker vi hvordan mål på flyt i pennbevegelser kan brukes til å vurdere bokstavforming hos begynnende skrivere. Vi diskuterer bokstavkarakteristikker som kan påvirke flyt og utfordringer knyttet til bokstaver formet av begynnende skrivere. Som svar på disse utfordringene viser vi at alle bokstaver kan segmenteres i rette og buede deler. Vi foreslår også hvordan forskere kan vurdere om bokstavdelene er produsert med tilstrekkelig nøyaktighet. Vi viser hvordan disse bokstavdelene kan analyseres på tvers av bokstaver og barn. Vi finner at barn produserer bokstavdelene med dårligere flyt enn voksne, og at unøyaktig bokstavdeler ble produsert saktere og med dårligere flyt enn nøyaktige bokstavdeler.

I den andre studien utforsker vi faktorer hos barnet som antas å påvirke bokstavproduksjonen. Det er godt etablert i litteraturen at barns evne til å forme bokstaver er assosiert med finmotorikk og bokstavkunnskap. Vi diskuterer kompleksiteten i ferdighetene som trengs for å forme bokstaver med god flyt. Vi finner at evnen til å kopiere bokstaver og

bokstavlignende symboler er forbundet med bokstavkunnskap og mer komplekse blyantoppgaver. Den motoriske utførelsen i bokstavforming påvirkes derfor av prosessering på høyere nivå, slik som gjenhenting av motorplaner for bokstaver.

I den tredje studien utforsker vi hvordan den leksikalske konteksten påvirker flyten i bokstavformingen. Igjen er det godt etablert i litteraturen at ordlengde og ordfrekvens påvirker skriftlig produksjon. Lange ord og lavfrekvente ord er mer utsatt for stavefeil, og korte ord og høyfrekvente ord er forbundet med raskere responstider. Vi diskuterer hvordan disse faktorene påvirker bokstavformingen hos begynnende skrivere. Vi finner at det ikke er noen forskjell i reaksjonstid når barn skriver ord til diktat, eller i flyt i pennbevegelsene i den første bokstaven i ordet. I tråd med tidligere forskning finner vi at lavfrekvente og lange ord mer utsatt for stavefeil.

For å konkludere, arbeidet i denne avhandlingen viser at det er mulig å vurdere flyt i pennebevegelsene i barns bokstavforming. Fremtidig forskning bør se nærmere på flyt i pennebevegelser når man søker å forstå den komplekse kaskaden av prosesser i bokstavformingen som må kombineres for å produsere tekst flytende.

Papers included in this thesis:

Paper 1 Fitjar, C. L., Rønneberg, V., & Torrance, M. (2022). Assessing handwriting: a method for detailed analysis of letter-formation accuracy and fluency. *Reading and Writing*. https://doi.org/10.1007/S11145-022-10308-Z

Paper 2 Fitjar, C. L., Rønneberg, V., Torrance, M., & Nottbusch, G. (2021). Learning handwriting: Factors affecting pen-movement fluency in beginning writers. *Frontiers in Psychology*, *12*, 1–13. https://doi.org/10.3389/fpsyg.2021.663829

Paper 3 Fitjar, C. L. (paper prepared for submission). Lexical processing does not affect motor execution within the word-initial letter when beginning writers write single words to dictation.

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1 Introduction

The ability to form single letters is a prerequisite for handwriting (producing text, with pen on paper[1]) and children's handwriting ability is found to predict composition quality (Berninger, 1999; Kent et al., 2014). However, we know surprisingly little about factors that affect beginning writers' single-letter writing, and in particular the fluency of their process of letter formation. Writing research rarely focuses on the single letter – single letter production is nearly always considered in the context of other letters, in real words or pseudo-words, but rarely alone. This thesis is an in-depth exploration of pen-movement fluency when beginning writers form single letters with pen on paper. From the literature on children's handwriting, three challenges with adjoining gaps can be identified with regard to this overall quest.

The first gap concerns how letter formation is measured, as well as the properties within a letter that might affect how we interpret such a measurement. In the existing literature, I found methods to assess legibility (for a review, see Feder & Majnemer, 2003) and methods to assess the letter-formation process (for a review see Danna et al., 2013). Product evaluation – that is, the assessment of neatness and legibility – is usually performed in context, with reference to other letters, and tends to relate to aspects such as overall consistency rather than specifying the necessary characteristics of each letter. Process evaluation – that is, the description and assessment of temporal, kinematic and dynamic aspects of handwriting – typically call for predetermined written samples, such as a specific letter or word. As far as I could see, there was no method to identify segments capable of being directly compared in terms of process regardless of how they were produced across letters; furthermore, such a method would need to include criteria for determining whether a segment was produced accurately or not. Here it should be pointed out that

[1] In this thesis, "pen" includes "pencil" unless otherwise stated.

different letter shapes are not constant in terms of their characteristics (Perret & Olive, 2019). For this reason, letter-level comparisons are problematic, regardless of whether the process measure used is based on duration or movement fluency. For instance, if size is kept constant, the letter V may have a shorter trajectory and require fewer shifts in direction than the letter M. Put simply, it may take longer to produce an M than a V because the M requires twice as many strokes and has a longer trajectory if size is kept constant, but that does not mean that the M is produced less fluently. The production of the two letters cannot be directly compared. To address this challenge, we need to explore those characteristics of manuscript[2] letters that make them unique. As regards cursive handwriting, it is common to isolate upstrokes, downstrokes and horizontal strokes (Meulenbroek & van Galen, 1990). Understanding how letters are composed of strokes that correspond to visual components of letters can be used to establish their "least common multiples" to identify letter features that can be usefully compared in terms of pen-movement fluency.

The second gap concerns child-level factors that contribute to fluent letter formation in children who are learning the letters. Studies that assess letter production in children who are learning to write tend to measure fluent production in terms of the speed of handwriting, operationalised as the number of letters produced during a time-limited task (Berninger et al., 1992). However, the time it takes to produce the required letters is not just a measure of pen on paper, but also of the time spent with the pen in the air between letters. It remains unknown how motor execution (i.e., pen-movement fluency) is affected by motor and literacy skills. Existing studies have varied greatly in that they have both focused on a wide range of motor skills associated with handwriting and targeted a wide range of tasks. Suggate et al. (2018) argue that, in

[2] Manuscript letters are handwritten letters that are not cursive. They may also be referred to as print letters.

between fine motor skills (i.e., bead threading and coin slotting) and writing skills (i.e., writing of a person's own name and of single letters to dictation) there is a special skill set that they call "graphomotor skills" (i.e., copying Greek letters). They recommend that fine motor skills *should* be explored using tasks that require pen operation, but at the same time they caution *against* using measures of fine motor skills that tap directly into the graphomotor component. Additionally, handwriting task typically involve writing words (Barnett et al., 2009) or writing all lower-case letters in alphabetical order (Berninger & Rutberg, 1992). These tasks require a broad combination of skills, thus conflate graphomotor skills and more literacy-oriented abilities that contribute to children's letter-formation abilities. To sum up, it remains unclear to what extent pen control and letter knowledge, respectively affect pen-movement fluency in various single-letter writing tasks in beginning writers.

The third gap concerns the lexical context in which a letter appears. For example, a letter's position within a word is likely to affect its production. Van Galen et al. (1986) find that mean velocity is higher for the second letter than for the first and third ones in pseudo-words written in cursive handwriting. The written production of high-frequency words differs from that of low-frequency words (Delattre et al., 2006; Kandel & Perret, 2015). Additionally, Afonso et al. (2015) find that, when a letter in a word corresponds to the most frequent pronunciation of that letter, it is written faster than when it represents a less frequent pronunciation. Thus, as far as proficient writers go, writing letters forming part of a word differs from writing each of those letters on its own. This is possibly because processing in writing words draws upon several processing modules that work in parallel, with each module starting to operate as soon as it is activated by receiving information from modules higher up in the system. If we know that this occurs in adults, it is worth asking whether it occurs in children as well. Unlike adults, who may split words into smaller processing chunks such as syllables (Sausset et al., 2012), children who are not yet proficient writers might process words sequentially, one letter at a time. In other words, a child writing the word CAR might not start processing for the A (e.g., identifying the phoneme and retrieving an allograph) until the production of the C is completed. However, this aspect remains largely unexplored. Even more clearly than in the case of adults, most of the literature regarding children is based on the analysis of spelling accuracy, reaction times and writing duration (e.g., Afonso et al., 2018; Søvik et al., 1996). Hence it remains unclear how the characteristics of a word, such as its length or frequency, affect pen-movement fluency in the word-initial letter written by beginning writers.

This thesis aims to fill these gaps by means of three separate papers. The first paper addresses the problem of letter-level comparisons and proposes a segmentation and coding scheme for manuscript-style letters. That scheme allows researchers to compare letter-formation processes across letters and writers. The second paper applies the method from the first paper in an analysis of pen-movement fluency to address non-motor literacy factors that might predict pen-movement fluency in single-letter production. Finally, the third paper addresses how word characteristics affect pen-movement fluency in the word-initial letter. Taken together, this investigation of the factors that affect pen-movement fluency in beginning writers forming single letters shifts the focus from a more generalised ability to produce single letters to the motor execution involved in letter formation. A better understanding of what affects that motor execution can contribute new knowledge about the processes involved when beginning writers form single letters.

1.1 A model of the writing process

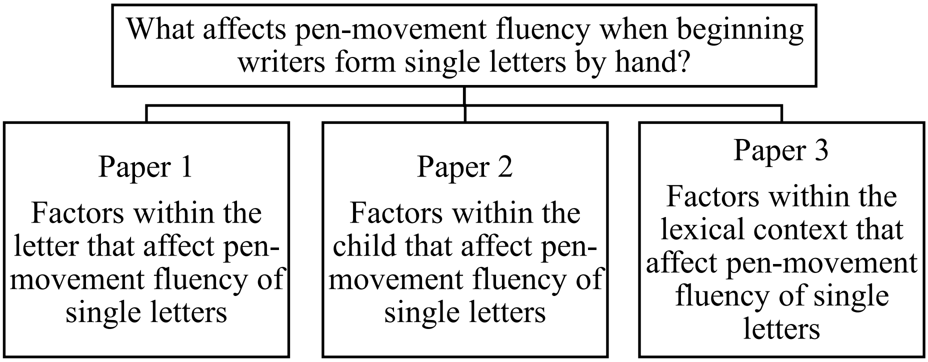
The theoretical framework for this thesis is the model of the writing process suggested by van Galen (1991). In this model, single-letter writing begins with an abstract letter representation and ends with the real-time trajectory of the pen moving across the page. According to van Galen, the modules are organised hierarchically, processing starting at the top and moving downwards in increasingly smaller units. Several modules can be engaged at the same time, in parallel. This allows the writer to start planning the next step, for example retrieving the spelling of a word, while modules on a lower processing level are still being executed in relation to a previously retrieved word, for instance to select allographs or make muscular adjustments. This is referred to as parallel cascaded processing.

In addition to providing a theoretical framework for explaining the organisation of the processes involved in handwriting, van Galen's work also provides a methodological framework for understanding letter formation above and beyond legibility or in the context of text production. Rather than focusing on reaction time alone, van Galen et al. (1986) argue that including an analysis of the ongoing performance (i.e., pen-movement fluency) can indicate whether increased demands on one or more higher-level processes affect reaction time only or cascade onto motor execution (i.e., lower-level processes).

1.2 The present studies

The main research question addressed in this thesis is the following: What are the factors that affect pen-movement fluency when beginning writers form single letters by hand? This overall question is broken down into three questions that explore the effects of factors within the letter, within the child's development and within the lexical context, as shown in Figure 1. Paper 1 uses van Galen's approach to pen-movement fluency to explore factors within the letter that may influence motor execution as measured in terms of pen-movement fluency. In Papers 2 and 3, van Galen's theory is applied to explore how the real-time formation of a single letter is affected by possibly competing processes on different levels, nested within the child and the lexical context, respectively.

Figure 1 *Main research problem and the three studies*



To be able to interpret how factors within the child and lexical characteristics of a word affect the pen movements in letter formation, we need to measure production. And to accurately measure production, we need to understand how factors within the letter may affect the measurement. For this reason, the research question brings forth two methodological issues:

1. What letter characteristics may influence pen-movement fluency as measured using counts of velocity maxima?
2. How can we measure the fluency and accuracy of single-letter formation?

Paper 1 presents a segmentation and coding scheme that allows researchers to compare real-time letter production across letters and writers. The scheme is based on theoretical expectations as well as previous studies of human movement and handwriting assessment. In short, we identify graphic features of prototypical manuscript letters whose real-time production can be usefully compared. We illustrate how the scheme can be used for research purposes by describing the velocity profiles of 27 adult skilled handwriters and 176 first-grade students with minimal handwriting training. We find that the children produced letter features less fluently and less accurately than the adults, and that the inaccurate features were produced more slowly and less fluently than the accurate ones.

Paper 2 explores how biophysical factors (e.g., pen control) and cognitive factors within the child influence pen-movement fluency in letter formation. In this study, the biophysical factor is restricted to a limited number of pen-control measurements and the cognitive factors included are various measures of letter knowledge. Two research questions are addressed: In children at the beginning stages of learning to write…

3. To what extent do factors associated with pen-control and with letter knowledge affect pen-tip movement fluency in copied letters and symbols?
4. After control for letter-copying ability, to what extent do factors associated with letter knowledge affect fluency when forming letters from dictation (i.e., in response to hearing letter sounds)?

The participants were the child sample from Paper 1. Their letter-writing ability was measured using a copy task (letters and unfamiliar symbols) and a dictation task (single letters). It is found that familiarity with letters generally affects pen-movement fluency in the copy task. Hence motor execution in letter formation is affected by processing on a higher level, such as the retrieval of a motor plan for an allograph.

Paper 3 explores how the lexical context affects pen-movement fluency in word-initial letters. The lexical context is limited to whether the letter is part of a word or is produced as a single letter as well as to characteristics[3] within the word known to affect the production of the

[3] Graphemic length and word frequency of words with a phonologically transparent orthography (meaning that they can be spelled correctly using the sub-lexical strategy, i.e., converting the individual phonemes into graphemes).

entire word through increased processing demands. The third paper addresses two questions:

5. To what extent do characteristics of the word to be produced (length and frequency) affect processing time prior to output onset?
6. To what extent, if at all, do length and frequency affect graphomotor performance (i.e., the fluency of pen movement) for the first letter once output has been initiated?

A sub-sample of the first-graders from Papers 1 and 2 participated in the experiment at the end of first grade. The children wrote single letters and words to dictation. The analyses show that pen-movement fluency in word-initial letter production is affected by whether the letter is produced on its own or is the first letter of a word: the letters were produced less fluently as single letters than as word-initial letters. Further, while word characteristics did not predict pen-movement fluency for the word-initial letter, they did predict spelling accuracy for the word. Thus, semantic processing appears to aid allograph selection and motor execution, but challenges in the spelling process appear to be dealt with after the word-initial letter has been fully formed. All in all, we find that pen-movement fluency in letter production is affected by letter characteristics, the child’s visuomotor skills and letter knowledge, and the lexical context for the letter.

1.3 Outline of the extended summary

The purpose of the present extended summary is to summarise and synthesise the issues and conclusions presented in the three papers in light of the main research question. The rest of this extended summary is organised in the following manner:

Chapter 2 places the research performed in a research context and provides the reader with background information from several branches of research on letter formation and handwriting. Chapter 3 outlines van Galen's (1991) model of the writing process, which is used to understand the processes involved in single-letter formation. Chapter 4 describes the overall research design used and methodological choices made in each study. The findings are summarised in Chapter 5 and discussed in Chapter 6. Chapter 7 discusses how the findings from Papers 2 and 3 contribute new knowledge about the relationship between pen-movement fluency and cognitive processes in beginning writers, thus directly speaks to the theoretical framework presented in Chapter 3.

2 Background

The empirical background to the research questions in this thesis extends from studies of motor skills and development to studies of cognitive skills and processes in writing. This chapter aims, first, to place the present research in the context of current knowledge about children's writing development and instruction; and, second, to present necessary evidence, from across those fields, to support each research question.

2.1 Children's writing development

Children's handwriting development starts before they can intentionally and accurately form single letters, and it continues well beyond those first strenuous letters until their handwriting is automated and stable. It is hard to say exactly when handwriting is automatised, but Bosga-Stork et al. (2016) find that, in a Dutch context, reading and writing skills correlate with handwriting speed in first and second grade, but not in third grade (age 9). This indicates that handwriting ability becomes an independent skill at this age. In a Spanish context, Afonso et al. (2018) find that the writing pattern of sixth-graders (age 11) is similar to the writing pattern of adults in terms of written latency and writing duration. For the purposes of the present thesis, however, age at automatisation is less relevant than the development leading up to the ability to recall and reproduce letters. It is sufficient to note that it seems rare for first-graders to have fully automatised their handwriting.

We must, however, bear in mind that what we assume to be a typical development is probably only typical within a specific cultural and historical context. Teale (1982) argues that literacy is a cultural achievement requiring either formal or informal instruction from the environment – not a universal achievement, which would be attained regardless of the environment. Children's handwriting development takes place within a culture that has certain expectations and norms for what constitutes good writing (Teale, 1982). This means that children learn how to read and write because they live in a society where writing has a function, and children acquire this skill in collaboration with people in their society. Given the recent switch in adults' daily writing habits regarding letters, notes, lists and signatures from writing by hand to various forms of digital writing, it would be worth asking – in another research project – how this change in practice might affect young children's understanding of writing.

With these caveats, the stages of typical development of writing can be summarised as progressing from the first intentional scribbles and marks made on paper at the age of 18 months or so to intentional letter formation in context with the purpose of communicating with a reader at the age of five years. This requires children to learn how to control the pen and to learn what to produce. In terms of motor control, Hay (1984) finds that children's movements tend to change from fast but inaccurate at five years to fast and accurate at nine years. In between, at seven years, the distribution of speed and accuracy is broader, making it difficult to say what are typical movements of this age group. In a comparison of four-, six- and eight-year-olds, the older children produced straight lines straighter, smoother and faster than the younger children (Contreras-Vidal et al., 2005). However, the visuomotor skills underlying handwriting ability develop rapidly around the time when children are five years old. Del Giudice et al. (2000) find that in children attending kindergarten in Italy, are able to copy non-letter patterns with 20 per cent accuracy at 4 years 6 months, but with 80 per cent accuracy six months later. Whether this is due to teaching efforts or to the natural development of visuomotor skills is not discussed.

For the purposes of this thesis, the shift from mere copying to forming letters from ideation is interesting, because this is the stage where children develop motor patterns for letters. Sulzby & Teale (1985) claim that scribbling is the first stage of emergent writing and is followed by single letters and strings of letters, then invented (phonological) spelling and, finally, syllabic and phonetic writing. They describe how a child (2 years and 11 months old) demonstrates what Puranik & Lonigan (2014) identify as conceptual knowledge and distinguishes between drawing and writing. At three years, they can "read" their own scribbles; and at three years and nine months, they can state which letter they intend to write. Children's first writing may have a logographic aspect in that the child associates the letter as a symbol with an idea unit rather than with a sound (Goodman, 1985). Logographic writing is often associated with children writing (or reading), for example, shop names without matching each grapheme to a phoneme. They may also remember the image of their own name and use that to write that name correctly while remaining unable to write any of the component letters in a letter-to-dictation task. This may explain why children often like to write the first letter of their own name or of that of people who are important to them (Bloodgood, 1999; Puranik & Lonigan, 2014). A plausible explanation might be that, to the children, that first letter symbolises the person rather than a sound.

Being able to match phoneme and grapheme (in an alphabetic writing system) represents a step towards procedural knowledge (Puranik & Lonigan, 2014) that draws upon the child's phonological awareness. However, awareness of the form of writing also plays a role in writing development (Bloodgood, 1999). When children first attempt to write letters (in contrast to scribbles), they may pay little attention to linearity or to the orientation of the letters (Myran, 2012). The final stages of emergent writing, according to Sulzby & Teale (1985), are syllabic writing and phonetic writing. Syllabic writing is when each syllable (or word) is represented by a letter, for example the letter *m* representing the syllable *me.* To read such texts, the reader must be familiar with the child and the context. Phonetic writing, however, is more transparent as each sound is represented by a letter. This clearly requires phonological awareness beyond the first sound of a word: the child must in fact be able to segment the word phonologically. At this stage, children may also be confused by letter names such as /ˈeɪ/ for *a*, /ˈbiː/ for *b* and /ˈsiː/ for *c*, which may trick the child into forgetting to write all the letters in *bin* and just write *bn*, because the /i/ sound is included in /ˈbiː/. Unlike in English, this only affects the consonants in Norwegian. Myran (2012) argues that parents, when introducing letters to their children, should use letter sounds rather than letter names from the beginning, in order to strengthen phonological awareness.

For the purposes of this thesis, letter writing is considered to develop from the copying of shapes to the recalling and reproducing of graphemes associated with phonemes.

2.2 The role of linguistic and education context in emergent handwriting

Reading and writing instruction varies across cultural contexts, both in terms of what elements are emphasised and in terms of when formal instruction commences. For example, French children are expected to be familiar with the movements required to form letters before they start first grade at the age of six, and they are expected to learn how to write in cursive in first grade (Bara & Morin, 2013). By contrast, Norwegian children do not receive any formal instruction in reading or writing before they enter first grade in the calendar year of their sixth birthday (Håland et al., 2018). However, this does not mean that Norwegian children have not encountered written communication before they enter school. The vast majority of Norwegian five-year-olds (97.8 per cent) attend a *barnehage*[4] (Norwegian Directorate for Education and Training, 2022). This is a form of pre-school mainly intended for children between one and five years; approximately 93.4 per cent of all children in that age span attend a *barnehage* (SSB, 2023). Attendance is socially expected but not compulsory. While no formal reading and writing instruction is

[4] This is sometimes rendered as "kindergarten" in English, even in semi-official translations, but as is clear from the description below, the *barnehage* is rather different from, say, the US kindergarten year.

given at the *barnehage*, children are encouraged to explore and play with language. The nature of this interest-based approach to literacy instruction before formal schooling and some implications of this are elaborated in the following paragraphs.

Even so, it is clear that children start formal schooling later in Norway than in other countries. As a consequence, the motor skills and emergent literacy skills that Norwegian children possess on school entry will have developed without the explicit instruction received by their peers in France or other countries where children start school much earlier. To those unfamiliar with the Norwegian context for early literacy education, I would recommend Hagtvet (2017), who provides an in-depth explanation. Since this issue falls outside the scope of the present thesis, I will limit my discussion here to those aspects that are crucial for the interpretation of the findings from the studies reported.

In the framework plan for the *barnehage* (Norwegian Directorate for Education and Training, 2018: 47–48), it is stated that “Staff shall invite the children to explore both spoken and written language” and “shall encourage children to play with language, symbols and text and stimulate their linguistic curiosity, awareness and development”. As far as I know, it is not documented how this is done on a larger scale. There are no official guidelines. However, resources are available online from the Norwegian Reading Centre (Lesesenteret, 2023) and the Norwegian Centre for Writing Education and Research (Skrivesenteret, n.d.). Further, the Agder Project, which is a research collaboration between the University of Stavanger Business School and the Norwegian Centre for Learning Environment (Centre for Learning Environment, 2021), explores how a more systematic approach to cultivating school-readiness skills through playful learning for five-year-olds can enhance their developmental trajectories, and this project has produced some support material for *barnehage* teachers. All in all, however, what children are taught and how they are encouraged to use written language at their *barnehage* depends on the specific institution and on its staff.

There are in fact some small, qualitative studies that explore some of the work performed by individual teachers to introduce children to various emergent literacy skills and to facilitate literacy events. In particular, it is common for group activities to be organised for the five-year-olds who are in their last year of the *barnehage*, to prepare them for enrolling in school in the following year. One such study by Hopperstad & Semundseth (2012) reports how one *barnehage* teacher works with a group of five-year-olds to stimulate their interest in writing by modelling the writing of single words using cardboard letters and by providing children with pencils and paper. One child is very eager to write and produces a long list of words, while another child produces long sequences of letters. However, the authors also point out that the teacher did not expect all children to write. A child who decided not to write, but instead chose to colour in a pre-made picture, was allowed to continue doing so. This highlights the implications of the wording of the framework plan, namely that staff are to *encourage* children to play with language. Thus, children who are already interested in language and literacy have ample opportunities to nourish their interest and hone their skills, while children who are less interested miss out on some of those opportunities (Hofslundsengen et al., 2016).

Considering that, when entering school, children in Norway will thus have been exposed to, and encouraged to explore, written language to a highly varying degree during the first five or six years of their lives, they come to school with varying literacy skills. Sunde et al. (2019) report that, at school entry, children in Norway are able to recognise, on average, 16.55 letters in a letter-sound recognition task where they hear the letter sound and have to choose one out of four upper-case letters on an iPad Fitjar et al. (2021) find that such children can recognise, on average, 18 out of 24 letters in the same phoneme–grapheme task (standard deviation: 5.6) and that they can correctly sound out, on average, 11 out of 24 letters when presented with lower-case letters (standard deviation: 6.8). Hence most children are familiar with half of the letters, but the standard deviations indicate that the normal range includes both some children who can match most phonemes to graphemes and many children who can match only a few phonemes to graphemes. In addition, there are children who cannot match any phonemes to graphemes when they start school. As noted above, there is thus a wide range in literacy skills among children first starting school in Norway.

The school curriculum for the Norwegian subject (language and literacy) includes competence aims to be attained after the second, fourth and seventh years of compulsory school (Norwegian Directorate for Education and Training, 2020). There are no specific aims for the years in between. For handwriting and typing, the competence aim after the second year is to be able to "write texts using pen and paper and using a keyboard". Because the curriculum must be interpreted and operationalised to suit the needs of the students, a significant amount of work is carried out at each school to adapt the aims set out in the curriculum (Ministry of Education and Research, 2016). The Norwegian Directorate for Education and Training provides some support materials online that teachers may use in this work and when preparing teaching plans. In addition, schools may develop local plans describing their reading instruction. However, a master's thesis (Waaler, 2022) found that those reading plans varied and that only 5 out of 40 plans examined included a description regarding the development of phonological awareness. Hodgson et al. (2010) found that most primary schools had local plans for each subject for each year but that their purpose may be to facilitate interdisciplinary projects rather than to describe the students' expected development in the respective subject. They also found that teachers tended to rely on the national curriculum and the textbook when planning lessons, and that lesson plans were rarely documented. It is therefore difficult to ascertain how schools ensure that children stay on their trajectories towards meeting the competence aims in due course.

Beginning reading and writing instruction in Norway has traditionally been dominated by an emphasis on phonics and the use of a bottom-up approach (Lie, 1991). Norwegian has a semi-transparent orthography (Seymour et al., 2003), meaning that most words can be read correctly by means of grapheme-by-grapheme decoding. This applies to both written forms of Norwegian: *Bokmål* (originally based on Danish) and *Nynorsk* (originally based on rural dialects). The semi-transparent orthography and the strong tradition for learning to read one letter at a time may explain the lack of focus on high-frequency words commonly seen in English-speaking educational contexts (where students have to grapple with a highly opaque orthography). The first letters that teachers introduce to children are S I L O R E M A; it is recommended to use lower-case forms (Bjerke & Johansen, 2021). Those eight letters allow the children to learn how to decode numerous short, orthographically transparent words such as *is* ('ice' or 'ice cream'), *si* 'say', *se* 'see' and *sol* 'sun'. In addition, they are able to read short sentences such as *Se sola, sa Ola* 'See the sun, Ola said'.

There is an ongoing shift in how – and, in particular, how fast – children are introduced to letters and writing in the Norwegian first grade. Teachers used to spread the letters of the alphabet out across the entire first year, but several schools have now implemented a rapid pace of letter introduction, in accordance with recommendations from the Norwegian Reading Centre (Sunde et al., 2019). Nowadays it is rather common to introduce at least two letters per week, and it is also recommended to combine the introduction of letters with meaningful and playful activities that include reading and writing (Lundetræ & Sunde, 2021). The rationale for faster-paced letter introduction is that it will give all children at least partial access to more letters sooner and also enable them to write more meaningful texts sooner. It is also argued that, because children are often familiar with letters when they start school, spending the entire first grade "re-learning" all the letters one by one can be demotivating. There is no official documentation indicating how many schools have shifted to faster-paced letter introduction, but a recent survey of writing in Norwegian first-grade classrooms found that children devoted most of their writing time to practising handwriting, mostly by forming single letters or writing single words (Håland et al., 2018), regardless of the pace of letter introduction. Thus, while the pace may have changed, the activities may not have.

Still, there is another – definite – change in Norwegian classrooms that calls for a change in how writing is taught, namely a shift in the writing tools used. The increased use of digital tools such as iPads and Chromebooks has sparked heated debates in social and other media among parents, teachers and researchers. Over the past five years, there has been a strong increase in the use of PCs, Chromebooks or iPads at Norwegian primary schools: in 2016, 13 per cent of teachers reported that their school provided each student with a digital unit; in 2021, 87 per cent said it did (Wagner et al., 2023). This quick increase coincides with the Covid-19 pandemic, when physical schools were closed down and there was an urgent shift to remote instruction. First-graders are a little less likely to be provided with a tablet, Chromebook or laptop computer, but the majority of them (approximately 77 per cent) do have access to such a digital unit (Gilje, 2023).

Because schools that use digital devices provide them to all children, it is less interesting for educational purposes whether children have access to such devices at home, which is likely to vary depending on the socioeconomic status of their families. However, how digital devices are included in instruction, and hence how they affect learning outcomes, is interesting from the perspective of the pursuit of better instruction. The aim of the DigiHand project (Gamlem et al., 2020) – of which this thesis is a part – is to contribute new knowledge about how the increased use of digital devices in first grade affect teacher–pupil interaction (Øvereng et al., 2022; Øvereng & Gamlem, 2022), the quality of children's texts and their writing development (Spilling et al., 2021, 2023). While those perspectives are outside the scope of this thesis and will not be discussed further, it is important to note that the sudden increase in the use of digital devices and typing even in first grade in Norwegian classrooms means that there is an ongoing change in how writing is taught in Norway.

The heated public debate about the use of pens versus iPads in first grade will probably continue, at least in Norway, for the foreseeable future. The core of that debate concerns what skills children need to learn and practise in order to become good writers. Among other things, it has been argued that children learn the letters better if they practise forming them by hand (Mangen & Velay, 2010). Assuming that this is correct, in order to optimise that practice we need to better understand the role of motor skills when children learn how to write letters by hand, and we also need to learn more about the cognitive and motor processes involved in writing letters as part of words. This thesis represents an attempt to provide new knowledge about factors that affect letter-formation fluency in beginning writers.

The remaining three sections of this chapter discuss what we already know about factors within the letter, factors within the child and factors within the lexical context, respectively, that affect letter-formation fluency. With regard to the first type of factor, there is in particular a need to address how letter production is assessed.

2.3 How letter characteristics affect the letter-formation process

It is clear from a review of the literature about the assessment of handwriting that it is difficult to compare handwritten letter production across letters because the letters are unique, and their production varies owing to letter-specific properties. A few studies explore how such letter-specific properties affect their production. Meulenbroek & van Galen (1990) explore the motor complexity of cursive letters by examining velocity patterns. The most complex letters were r and z, because of their horizontal waveforms when written in cursive. Those letters, when written by children in grades 2–6, were produced with a lower mean velocity and had more changes in velocity. Karlsdottir (1996b) explored letter-production accuracy, finding that children were least accurate when writing the letters f and g, both in cursive and manuscript-style script. However, as pointed out by Stefansson & Karlsdottir (2003), whether this is due to the nature of the letters or to teaching efforts is unclear.

Letter production may be described and assessed, for various purposes, from the initial scribbles of the beginning writer and throughout life, even when handwriting ability may have deteriorated for medical reasons, such as owing to Parkinson's disease (Broderick et al., 2009) or a stroke (McCloskey et al., 2018). Hence there exists an array of methods to assess letters and their production, each serving a different purpose. However, I found no method that enabled comparison of the production of any two different letters.

A general analysis of the various methods shows that, in short, letters can be described based either on the written product or on the process. The assessment of the written product can be either holistic (i.e., with regard to overall legibility) or analytic (comparison against an ideal sample).

With a focus on legibility, there are several tools for evaluating handwriting that allow researchers and practitioners to assess legibility and neatness (for a review, see Feder & Majnemer, 2003). However, methods that focus exclusively on the final product of writing are not adequate for exploring children's handwriting development, since they will conceal how consistency in pen movement in the letter-formation process also develops as children grow and become confident in their handwriting skills.

The process-focused measures can also be broken down into two categories. Measures of letter-writing fluency may refer, for example, to how many letters are produced in a minute (Berninger & Rutberg, 1992).

Further, digitised pen traces and kinematic measures of handwriting enable separate analyses of pen on paper, pen slightly above paper and pen away from paper (Afonso et al., 2018; Paz-Villagrán et al., 2014). Afonso & Álvarez (2019) find that there is a lack of consensus in the field on how best to measure the dynamics of the writing process, causing researchers to use a wide array of measures. In their discussion, they focus on temporal variables such as whole-word durations, inter-letter intervals, mean stroke durations and letter durations. They suggest that, to circumvent the apples-and-oranges problem of comparing letters with unique properties (such as different trajectories and required pen lifts), experimental designs should compare only "the same letter (or letters) in the same position in different words" (Afonso & Álvarez, 2019: 156). However, since this restricts the variables that can be manipulated in an experimental design, it limits the possible research questions. Instead, I argue that we should take a step back and explore the opportunities to develop a new method that would allow cross-letter comparisons.

Several kinematic measures based on time-course data are used in handwriting research (Danna et al., 2013), each reflecting how the pen moves on paper. In brief, time-course data derive from specially developed software and reflect the movement of the pen as a person writes either with a digital stylus on a sheet of paper overlayed on a Wacom Intuos digitising tablet or with a smart pen and special paper (Eye and Pen by Alamargot et al., 2006; Ductus by Guinet & Kandel, 2010, MovAlyzR by Neuroscript, n.d.; OpenHandWrite by Simpson et al., 2021). For example, the OpenHandWrite software captures the position of the stylus every 4 or 5 milliseconds (depending on the specifications and settings of the tablet), both on the surface of the tablet and in the air just above it, using a Cartesian co-ordinate system with time stamps. This makes it possible to calculate the velocity of the stylus between any two data points. Kinematic fluency measures usually reflect changes in velocity, for example in the form of mean velocity, number of peaks of velocity or jerk (peaks in rate of acceleration). To obtain meaningful results, the raw data must be filtered, usually to remove movement noise (Marquardt & Mai, 1994; van Galen et al., 1993), so that what remains is a measure reflecting the writer's ability to move the pen fluently. Exactly how to filter out measurement noise so that the data we submit for analysis represent the variation within the writer is a research field of its own, and it is not within the scope of this thesis to investigate this any further.

One of several fluency measures based on kinematic profiles of pen movement is the number of velocity maxima per pen-trajectory between point A and B. This is a simple measure, and it is suitable for describing pen movement without any prior assumptions about good and poor performance. Signal-to-Noise velocity peaks difference (SNvpd) is a more complex measure that captures the fact that even in maximally fluent handwriting, some velocity peaks are necessarily occur. Danna et al. (2013) argue that it is suitable for identifying the locations of disfluencies in pen movement. To obtain it, they filter the raw data twice using a fourth-order low-pass Butterworth filter, once with a cut-off frequency of 5 Hz and once with a cut-off frequency of 10 Hz, and then count the number of remaining velocity peaks in each filtered output. The 5 Hz filter is stronger than the 10 Hz filter, meaning that it filters out more peaks. Next, they calculate the difference between the two outputs. In their view, the remaining peaks are supernumerary and thus represent abnormal velocity fluctuations. Fluent production will not have any peaks when measured with SNvpd. However, one objection to both the simple and the complex measure is that without reference to *what* (i.e., what letter, on its own or in what word) is being produced, *how* it is produced (i.e., the process) does not really tell us much about the person's handwriting ability.

As pointed out at the beginning of this section, the literature review regarding the assessment of letter formation shows that everyone agrees that the letters are unique and that it is therefore not possible to make fully valid comparisons across letters. However, this uniqueness has been explored only to a limited extent. Changizi & Shimojo (2005) explore the complexity of writing systems with regard to character length (i.e., the number of strokes per character) and redundancy (put simply, how many strokes are essential for the letter to remain unique). Strokes are identified as movements: "strokes are separated by discontinuities so that 'U' is one stroke, but 'V' is two and [...] stroke junctions are decomposed into their constituents so that 'T' and 'X' junctions possess two strokes" (Changizi & Shimojo, 2005: 272). To make progress on this point and enable across-letter comparisons, we need to address the "letterness" of letters and explore this uniqueness in order to develop more suitable methods for assessing handwritten letters, which can then be applied to improve our understanding of how children's motor skills and letter knowledge affect the letter-formation process.

2.4 How motor skills and letter knowledge influence the letter formation process

A review of the literature from several different academic fields including occupational therapy and neuropsychology, all of which have contributed towards our general understanding of what a child needs to successfully produce handwritten text, shows that studies within occupational therapy mostly focus on children's visuomotor skills, that is, their pre-writing skills such as the ability to draw different shapes. This may be measured using the Developmental Test of Visual Motor Integration (Beery & Beery, 2010), and children's scores on that test correlate with their ability to copy letter forms (Weil et al., 1994). This indicates that letter copying taps into, at least partially, the same skills as the tasks in the Visual Motor Integration test. In contrast, children's text quality is found to correlate with their ability to reproduce the alphabet quickly and in correct order using lower-case letters (Berninger, 1999).

For first-graders, orthographic coding[5] contributes directly towards handwriting ability[6] (Abbott & Berninger, 1993). In terms of writing development, these two perspectives represent the two ends of a normal-development trajectory, one of which does not require writing at all while the other requires fairly advanced writing skills. From these and similar studies of children's handwriting ability, it is possible to identify an assumption in occupational-therapy research to the effect that a child's ability to form single letters has a motor component (i.e., being able to physically move the pen) and a cognitive letter-knowledge component (i.e., having an idea of what to produce), and that successful output requires the combination of these components. In line with this, the rationale for the second paper in this thesis stems from a lack of knowledge about how factors within the child, such as motor ability and letter knowledge, affect pen-movement fluency in motor execution when beginning writers form single letters.

2.4.1 Motor skills in handwriting

Handwriting requires finger, wrist, and arm movements to be combined (van Galen, 1991), meaning that there is clearly a motor aspect to handwriting. When there is an issue with handwriting performance, it might be reasonable to assume that the cause is (or at least may be) related to the co-ordination of those movements. Indeed, in some countries such as the US and the UK, children with poor handwriting are often referred to occupational therapists (Cornhill & Case-Smith, 1996; Nightingale et al., 2022). In this context, "poor handwriting" is understood as poor legibility and/or slow production, and legibility and pace of production are indeed outcome measures in several occupational-therapy intervention studies (Hoy et al., 2011). With regard to legibility,

[5] The tasks are described as deciding if two words that are shown in succession are identical and deciding if a given letter appeared in the word last seen.

[6] As measured in terms of accuracy during the first 15 seconds of the alphabet task and a paragraph-copying task

several handwriting-evaluation tools have been developed to enable researchers and practitioners to track development over time (for a review, see Feder & Majnemer, 2003).

When handwriting is perceived mainly as a motor skill, illegible output is assumed to be due to sensorimotor or perceptual problems. Occupational-therapy interventions aimed at improving handwriting legibility therefore typically have a motor focus, which includes strength, grip and fine motor skills (Piller & Torrez, 2019). However, the interventions do vary in whether they address what are assumed to be underlying problems, such as visual perception and motor co-ordination, or instead address handwriting directly, for example by means of therapeutic practice such as writing to dictation or copying, which is claimed to yield better effect (Nightingale et al., 2022). These findings are in line with an earlier review by Feder & Majnemer (2007), who claim that children's ability to produce the letters of the alphabet quickly and legibly is likely to be affected by factors other than their motor skills. Thus, while some children may of course benefit from fine motor or visuomotor interventions, explicit handwriting instruction is generally more effective in improving the legibility and speed of children's handwriting, and it is clear that poor handwriting may have other causes than inadequate fine motor skills.

The motor skills needed for handwriting can be broken down into several categories. Erhardt & Meade (2005) discuss gross motor skills (e.g., posture), fine motor skills (e.g., fixation at the wrist, elbow and shoulder) and oculomotor skills (e.g., controlling the extraocular muscles, visual perception and visuomotor maturation) separately. They particularly emphasise that deficiencies in gross motor skills will cause fatigue and a consequent inability to co-ordinate the smaller muscles. Children who do not sit "properly" when they write – with their feet on the floor, their hips at a 90-degree angle and good pelvic and spinal alignment – may grow tired sooner, and their handwriting may then deteriorate because it becomes harder for them to maintain an even pencil pressure using fine motor skills and a good downward visual gaze. The fine motor skills in question require “finger dissociation and grading of muscle activity during pencil grasp [to] be coordinated with fixation at wrist, elbow, and shoulder” (Erhardt & Meade, 2005: 199). The relevant oculomotor skills involve visual perception and visuomotor integration – in other words, being able to see a shape and then draw it (Erhardt & Meade, 2005).

Visuomotor integration (or control) is often tested using the Developmental Test of Visual Motor Integration (VMI) (Beery & Beery, 2010). In that test – according to McCrimmon et al. (2012) – visual skills are understood as visual-perception skills while motor skills are understood as motor co-ordination. Further, visual perception is operationalised as the ability to identify, for example, body parts in a picture or to identify which printed figures are identical. Motor co-ordination is the ability to move the pen from dot to dot. In other words, the ability to move the pen intentionally on the paper appears to be a separate sub-skill within visuomotor integration. In a Taiwanese context, visuomotor integration and motor accuracy have been found to predict legibility in third- to fifth graders (Tseng & Murray, 1994). Suggate et al. (2016) distinguish between fine motor skills (operationalised as the ability to post coins into a slot, thread beads and trace through a maze) and graphomotor skills (copying Greek letters, rated for accuracy), finding that graphomotor skills – but not fine motor skills – predict better decoding skills in pre-school children. Graphomotor skills obviously include fine motor skills, namely those used for writing, but this finding suggests that they may also include other components, such as abstract letter knowledge, which may play a crucial role in letter formation.

In the field of neuropsychology, some studies of handwriting focus on how different types of brain damage affect patients’ ability to write, especially that of patients who have suffered strokes and therefore have some form of brain damage. From these studies, we know that people who have suffered strokes may be able to spell orally but not in writing (McCloskey et al., 2018), or they may be able to copy text but not write to dictation (Rapp & Caramazza, 1997). McCloskey et al. (2018) argue that the reason the patient in their study misspelled words in writing is that the patient's graphomotor buffer was damaged. The graphomotor buffer is where phonemes are matched with motor plans for allographs. Damage in this area affects the ability to form or hold an abstract motor plan for letters, and this is assumed to cause the deterioration in handwriting proficiency. On a purely motor level, Mai & Marquardt (1994) find that a patient who has suffered a cerebellar stroke cannot produce letters with fluent pen movement but can produce superimposed circles with fluent pen movement. Their interpretation is that the ability to draw circles reflects a preserved potential for automated movements which the person may not be able to realise when writing. Again, this suggests that the small muscles controlling the fingers are not solely responsible for the motor-execution aspect of forming a letter.

Other studies have questioned specifically whether the motor plan is linked to the muscles in a specific effector (e.g., the right hand). Rijntjes et al. (1999) explore brain activity when adults sign their names and when they perform zigzagging movements. Both tasks were performed using both the right (dominant) index finger and the right big toe. The authors find that motor plans (or "movement parameters", in their terms) are coded to limbs but are functionally independent. In other words, the toe can do the job of the finger and move accordingly. Based on this, Wing (2000) argues that it is therefore likely that letters are stored as abstract movements with relative positions and spatial directions. The size and speed of motor execution may not be determined until the writer has decided which limb (effector) to write with.

2.4.2 Transcription and graphomotor abilities

Letter formation is part of the broader skill set of transcription (with pen and paper), but the two terms cannot be used interchangeably, because transcription can also be, for example, typing on a keyboard or even producing Morse code with smoke signals. Output production thus represents only part of transcription. The part of the writing process that Berninger (1999) and Hayes (2012), who confine themselves to the pen-and-paper context, refer to as transcription includes everything from the retrieval of spelling to the writing of words on the page. The transcription part is considered a critical factor for children's ability to produce text, but until the 1990s it was largely ignored in studies of the writing process in adults because adults are assumed to have automatised allograph selection and the motor execution (Hayes, 2012). Any differences in written composition quality were therefore explained with reference to higher-level processing such as planning, text generation, revising and reviewing (e.g., Levy & Ransdell, 1995). However, later studies have found that adult transcription is also affected by word characteristics. This will be further discussed in section 2.5. In beginning writers though, transcription is assumed to represent the main obstacle in text production. This explains at least partially the overwhelming focus on transcription skills observed in research into beginning writers text composition.

In the literature, children's ability to combine motor and cognitive processes is variously referred to as graphomotor skills, visuomotor integration and fine motor skills; in all cases, this ability is assumed to reflect handwriting readiness (Dinehart, 2015), and the emphasis on motor skills is evident in all three concepts. Further, they are in fact used interchangeably in the literature (Suggate et al., 2016) as they are all assumed to be "small muscle movements that require close eye–hand coordination" (Luo et al., 2007: 596). Suggate et al. (2016) argue that the concepts of graphomotor skills, handwriting skills and fine motor skills are all used to describe the part of handwriting that is not cognitive skills. However, they emphasise that fine motor skills become graphomotor skills when used for letter writing.

Consistent with the strong focus on the motor aspect, transcription skills are often assessed using writing tasks that do not require the writer to think of something to write (ideation) or to plan the text. Researchers exploring transcription skills may provide their participants with stimuli for written naming, have them spell to dictation or have them copy written text (Bonin et al., 2015). While the intended target outcome of all three task types is the same, namely a single written word, it should be pointed out that the writer needs to apply different sets of skills in each task, each drawing upon different resources. The choice of task therefore has implications for the conclusions one may reasonably draw based on the data gathered. Written picture-naming tasks are often used to understand how words are retrieved. In such a task, the participant must first recognise the object, then activate semantic information, then recall the lexical word associated with the picture, and finally recall and execute a motor plan (Torrance et al., 2018). Dictation tasks are often used to assess spelling skills. Unless their purpose is to detect what words a participants can and cannot spell accurately, dictation tasks demand a certain level of spelling proficiency in the participants. Several studies have used spelling to dictation to explore what characteristics make words more difficult to spell. Finally, copy tasks are often used to assess graphomotor performance. This might be based on the assumption that, because the spelling is provided, the need for lexical processing is so reduced that the output reflects only the writer's ability to form letters. However, and in particular for younger writers, the reading of the stimuli has been shown to affect the writing-onset latency (Afonso et al., 2018).

In primary-school children, handwriting ability is often assessed using an alphabet-writing task (Berninger & Rutberg, 1992). The child is instructed to write all the letters of the alphabet in correct order using lower-case manuscript letters. The researcher marks with a slash after the last letter the child wrote every 15 seconds. This task may give the teacher an indication of how well the children are able to form each letter – both if they can remember what to write and in what order, and how fast their production is. As can be expected, children's scores on the alphabet-writing task are linked to their composition skills (e.g., Kent et al., 2014; Reutzel et al., 2019) – slow production is associated with poor text quality (Berninger, 1999). Other tasks used to measure letter-formation ability include copying sentences where the words are scrambled (Reisman, 1993) or copying a short story (Karlsdottir, 1996a; Phelps et al., 1985).

How graphomotor skills are best assessed depends on the purpose of a study. If it is to understand why some people struggle with the motor execution of handwriting, it is necessary to keep the cognitive load constant (Séraphin-Thibon et al., 2019). By contrast, if the purpose is to assess the mental processes involved, it is necessary to keep the motor load constant. As discussed in Section 2.3, letters vary in complexity and hence presumably in the motor load they cause, and their kinematic profiles also vary. Hence across-letter comparisons appear to be problematic. However, as I argued in that section, once these issues have been identified, there are ways to deal with them. Study 1 in this thesis, Fitjar et al. (2022), describes a method for segmenting letters and coding them for accuracy with the purpose of developing a direct measure of pen control in letter formation. Using such a method, graphomotor performance can yield more detailed information about the writing process than more educationally oriented measures are able to provide.

In this thesis, the concept of graphomotor skill is used to capture "the ability to take a mental representation of a figure and reproduce it on the page" (Fitjar et al., 2021: 9). Hence it is not limited to the recalling of letters, for example in response to dictation or from memory in response to a stimulus, and nor is it limited to visuomotor integration, which is what a copy task requires. However, if the child is to look at a figure, hold a mental representation of that figure and then reproduce it on paper, this also requires visuoperception skills. What is more, graphemes differ from (other) geometric shapes in that, for skilled writers, they are associated with an extra layer of information – an abstract representation of an allograph along with a motor plan (McCloskey, 2023; Wing, 2000). This additional information might influence motor execution in letter formation but not in the formation of geometric shapes – hence *grapho*motor. Such an abstract allographic representation is captured by cognitive psychological approaches to handwriting and letter formation where the focus is on the many mental processes that are necessary in written production. Once we better understand the motor and non-motor processes involved in single-letter formation, we can draw upon this knowledge to explore to what extent the letter-formation process is influenced by the characteristics of the words that the letters are part of.

2.5 Is the letter-formation process affected by the lexical context?

In terms of the writing development described in Section 2.1, being able to recall and reproduce the correct letters to write a word is a sign that a child has come a long way in his or her writing development, as several processes must be combined to write a word. With the exception of targeted letter-formation practice where children produce the same letter repeatedly, letter formation usually happens within a lexical context. It is a reasonable assumption that this lexical context may affect children's letter-formation process in single-letter production, given what we know about the single-word writing process in adults. In short, the writing process in adults is a cascade of cognitive processes where a process starts as soon as it is sufficiently activated by the preceding process (Olive, 2014; van Galen, 1991). For example, as soon as a phoneme has been identified as being part of a word, the process to recall the appropriate allograph begins right away, although the process of identifying the other phonemes in that word is still ongoing. In adults, all of this happens really fast, to the point that we do not even consciously think about spelling and allograph selection – unless the word is difficult to spell, in which case the process may be interrupted and letter formation may appear disfluent (Lambert et al., 2011). The evidence for this is that spelling accuracy is lower for some words than for others (Søvik et al., 1996). To children who have not yet become proficient writers, by contrast, most words are at least a little difficult to spell, simply because the child has not yet automated the spelling process. Beyond this, the issue of to what extent the characteristics of the words involved affect the letter-formation process in beginning writers is a very under-developed area of research.

One relevant question to ask in this connection is the following: What can pen-movement fluency tell us about the processes occurring when beginning writers write single words to dictation within a semi-transparent orthography? This question rests upon four assumptions that must each be addressed. First, why do we believe that the manipulation of lexical characteristics can tell us anything about the processes in writing? Second, why do we believe that information about pen-movement fluency may contribute new knowledge? Third, why do we believe that orthography is a relevant factor? And fourth, why do we believe that the processes in writing may be different in children (or other beginning writers) from those in adults (or other proficient writers)?

The manipulation of lexical characteristics is used to investigate the writing process. Studies of single-word handwriting behaviour have found that when adults write, the writing process is affected by the type of words they write. González-Martín et al. (2017) find that graphemic length – which appears to be synonymous with the number of letters in a word – determines onset latencies. Álvarez et al. (2009) find that inter-letter intervals (i.e., the time between letters) are shorter within a syllable than between syllables, arguing that this is because the writer processes language (in this case Spanish) by syllables, meaning that the syllable constitutes a unit. Similar studies conducted for French (Kandel et al., 2006) and German (Hess et al., 2018) support the argument that, in adults, syllables represent one type of processing unit in writing. Baus et al. (2013) find that writing latency was delayed for low-frequency words whereas word writing duration was not affected when Spanish-speaking adults responded to a picture-based typing task. Delattre et al. (2006) find that, for adults (writing in French), it takes longer both to start writing and to complete writing words with an irregular spelling. Because the writing process thus seems to be different in words that differ in the regularity of their spelling but are matched with regard to other characteristics and therefore capable of being compared, we can assume that the difference in production can be ascribed to a difference in how the words are processed.

Exploring pen movements in written production may contribute new knowledge about the writing process, because moving the pen on the paper is the last of the processes in handwriting. Van Galen (1991) argues that the processes in handwriting happen in parallel and are cascaded rather than sequential. The general idea of cascading processes is a necessary basis for any argument to the effect that word characteristics may even potentially affect pen-movement fluency. As demonstrated in the previous paragraph, we know that word characteristics affect not only the processes preceding the first pen (or key) press, but also those subsequent thereto. However, as the examples show, most of the studies referred to have explored the time between key presses or the time taken to produce whole words. The latter measure may include time spent both on and off paper. Afonso et al. (2020) explore how different word characteristics affect writing duration in children with developmental dyslexia (DD), children without DD matched for chronological age and children without DD matched for reading age. For natural reasons, the children matched for reading age were younger than those in the other two groups. The authors find that the younger children took overall longer to write words but that there was no difference in time spent with the pen in the air across the three groups. This suggests a difference in motor execution. A study of differences in pen-movement fluency would explicitly explore to what extent motor execution is affected by word characteristics for different groups of writers. In this connection, it must be kept in mind that there are two main possible explanations for why motor execution may not necessarily be affected by previous processes: either the final processes are encapsulated in a module and hence insulated from the preceding ones, or the entire writing process in beginning readers is sequential rather than parallel and cascading in nature.

Afonso et al., (2018) find that children writing in Spanish required more time to process low-frequency words than high-frequency words in a copy task, but not in a spelling-to-dictation task. The difference in the children's latencies in the two tasks might pertain to the input level. With regard to output, the authors find that the effect of word frequency on writing duration disappeared at some point between second and sixth grade. A plausible interpretation is that allograph selection and motor execution have evolved into an (at least almost) encapsulated module towards the end of primary school and are therefore no longer affected by previous processing. However, a method allowing separate measurement of allograph selection and motor execution may contribute new knowledge about the extent to which motor execution is affected in beginning writers and about what effects can be ascribed to allograph selection in such writers.

An alternative explanation is that pen-movement fluency is not affected by word characteristics when beginning writers write single words to dictation because each process is completed before the next one starts, meaning that processing takes place sequentially. In that case, writers will either recall the spelling of the entire the word along with the motor plans before the first pen press, or else recall the allograph and execute the corresponding motor plan letter by letter. Ellis (1982) describes how the assembly of graphemes may follow either a lexical route or a sub-lexical route. Through the lexical route the orthography for the entire word is recalled. Words assembled through the sub-lexical route rely on each phoneme being converted to a grapheme. In languages with a shallow orthography, such as Spanish or Italian (Seymour et al., 2003), spelling through the sub-lexical route will almost always result in a correctly spelled word. In these languages, most words can be spelled correctly by simply sounding out a word and segmenting it into phonemes. The word [teˈneɾ] in Spanish is an example of a word that can only be spelled with the graphemes *t e n e r*. None of the phonemes can be realised with alternative graphemes. Words assembled through the lexical route are accessed as one unit from memory. In languages with an opaque spelling, such as English, most words cannot be spelled correctly through the sub-lexical route alone. In order to spell [tʰu̟ː] correctly in English, the writer needs to know the context, since that sound sequence can be realised graphemically as either one of the three words *two*, *to* and *too*, which have different meanings. Thus, in order to successfully spell the word *two* in "I was two years old", the writer probably needs to retrieve the graphemes *t w o* as one lexical unit. It should be noted that spelling is often performed using a combination of the two strategies (Sheriston et al., 2016).

We would expect to see a difference in writing onset between high and low frequency words and between short and long words but not in motor execution if the entire word had been prepared using the lexical route before the first pen press. If spelling is done strictly letter by letter using the sub-lexical route, by contrast, there would not be a difference in writing onset between words with different characteristics as long as the word initial letter remained the same. Sounding out /k/ in *cat* would not take longer than /k/ in *can* because the sound is the same and the motor execution would also be similar.

Lété et al. (2008) find that spelling accuracy in French is affected by word frequency even in first grade and that this effect increases significantly between first and second grade. They argue that this may be explained by the inconsistency of French orthography, which does not allow writers to achieve an accurate spelling by assembling the phonemes one by one, thus relying on the sub-lexical route alone, meaning that they instead need to remember and recall the entire word using the lexical route. This is in contrast to languages with fairly transparent orthographies, such as Spanish and Norwegian (Seymour et al., 2003), with regard to which children are taught from the beginning to sound out words when they write. Søvik et al. (1996) find that

Norwegian fourth graders differed little in spelling accuracy when writing frequent versus infrequent words. However, there was a significant interaction effect of frequency and length such that short and highly frequent words were more accurately spelled. Even in a language with a transparent orthography such as Spanish, where it is possible to spell words correctly relying on the sub-lexical route, children are prone to make more spelling errors in longer words (Sánchez Abchi et al., 2009).

The interaction effect of word frequency and word length on spelling accuracy is most likely associated both with the transparency of the orthography and with the age of the children. In a cross-linguistic study, Marinelli et al. (2015) find that, in both younger and older English children, spelling inaccuracy increased with word length for both low- and high-frequency words, but older English children spelled high-frequency words more accurately regardless of their length. The pattern for Italian children was less clear, as they overall spelled more accurately regardless of frequency or length. That study demonstrates that, in languages with a transparent orthography, children can – and do – rely on the sub-lexical route to achieve accurate spelling of both non-words and real words with different levels of difficulty. However, the "younger" children were 7–8 years old and thus had some writing experience, and the focus was on spelling accuracy.

As discussed in Section 2.4.2, transcription includes both allograph selection and motor execution. In adults, transcription is assumed to be automatised and thus not to constitute a bottleneck for written output. In beginning writers, by contrast, transcription may be such a narrow bottleneck that it forces all other processes to wait (Hayes, 2012). Exploring to what extent pen-movement fluency in single-letter formation is affected by word characteristics can contribute new knowledge about motor execution in letter formation in beginning writers. Distinguishing between allograph selection and motor execution could shed new light on the role of forming letters with pen on paper for beginning writers as well as contributing to the theory about writing processes.

3 Theoretical framework

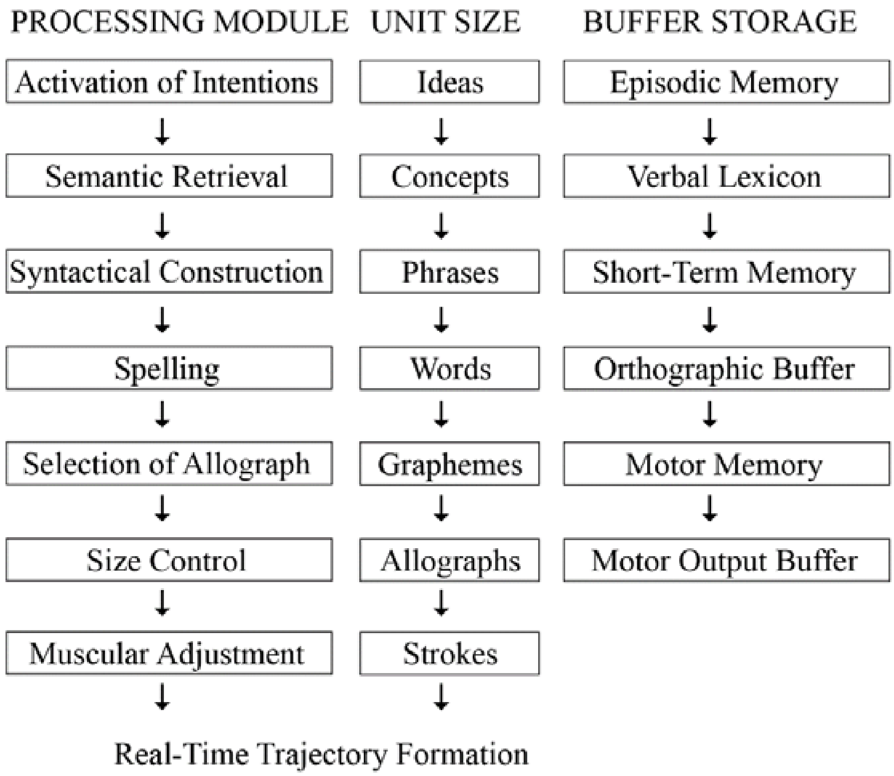
"[L]etter formation should not be seen as biophysical processes only. Indeed, cognitive variables such as linguistic and lexical complexity, word and letter length, and other contextual factors significantly interfered in real-time production" (van Galen, 1991: 184).

In this chapter, I will describe van Galen's (1991) model of the writing process, which is the theoretical framework underpinning this thesis. That model identifies all the sub-processes involved in letter production and allows us to theorise around how these sub-processes are organised and how information flows between the different levels. For the purpose of the theoretical contributions of this thesis, the emphasis will be on modularity and on parallel and cascaded processing.

The production of a letter starts with an abstract letter representation and ends with the real-time trajectory of the pen moving across the page, as shown in Figure 2. In his paper, van Galen states the following (1991:181–182):

> (1) Handwriting is the outcome of several different processing modules, each of which addresses a specific feature of the message.
> (2) The architecture of these modules is hierarchical in the sense that output from each stage forms the input for the next lower stage.
> (3) From the the [*sic*] top to the lower stages of the hierarchy processing units decrease in size.
> (4) All modules are engaged in processing activities concurrently. However, higher modules are further ahead to real-time output than lower modules.
> (5) To accommodate for time frictions between modules storage buffers allow the transient buffering of stage output.

Figure 2 *Model of the writing process suggested by van Galen (1991: 183)*



In other words, the processing modules involved in handwriting are organised hierarchically, starting at the top and moving downwards to increasingly smaller units. Processing happens in a parallel manner, not sequentially as a series of processes. Further, the processing is cascaded, which means that once a process, such as allograph selection, is sufficiently activated by the previous process, in this case the spelling module, processing by the allograph-selection module begins. Viewed from the opposite perspective, this also means that allographs are not selected until spelling has been at least partially retrieved – but note that this does not mean that the entire spelling of a word must be completed before allographs are selected, as would be the case in sequential processing. In parallel cascading processing, several modules can be engaged at the same time, which allows the writer to start planning the next step, for example by retrieving the spelling of a word, while modules on a lower processing level, such as those for selecting allographs or making muscular adjustments, are still being executed in relation to the previously retrieved word.

3.1 Modularity

According to van Galen (1991), the processes involved in handwriting have a modular architecture. This means that certain actions together constitute a process which is to some extent separate from the other processes. One example is spelling, which is possible to perform without the processes involved in allograph selection or even semantic retrieval. Especially in transparent orthographies, it is *possible* to spell a word correctly to dictation solely by means of phonological analysis. However, purely phonological spelling requires a great deal of effort. When the writer is familiar with the words' meaning and its orthography, spelling is probably then influenced by the semantic and orthographic processing of a word. Hence the spelling module may be more or less closed off from the other processes.

The idea of modular processing units was proposed by Fodor (1983) in a theory on the modularity of the mind. Fodor discusses input modules at length, but his discussion of central systems and output is limited. In his view, the input modules are informationally encapsulated – in the sense that the processes within one module will not be interrupted by other processes – and domain specific. By contrast, the central system is not domain specific and therefore, by definition, is not informationally encapsulated (Fodor, 1983). Hence any processes in writing that require central processing cannot be informationally encapsulated either.

3.2 Processing levels

The processes considered central to handwriting are usually those pertaining to the retrieval and activation of orthographic representations, while the processes that regulate motor responses are referred to as peripheral processes (Afonso et al., 2015). Similarly, van Galen claims, with regard to his model of processing modules, that "[m]otor processes play a role in the model below the spelling module" (van Galen, 1991: 184). Hence it might be tempting to label allograph selection, size control and muscular adjustment as peripheral processes. However, a different way of interpreting the distinction between central and peripheral processing is that it depends on the amount of attention that is needed to complete the processing task and the interaction between the task and other tasks. Motor processes, on the other hand, may be perceived as happening "automatically", "without thinking", and this is because, with sufficient practice, motor activities may be processed peripherally. This raises the question of the flow of information between central and peripheral processing. If motor processes truly are processed without interference from higher-level processes, they may be part of an encapsulated module. As soon as the module has received the necessary information, no additional information is needed to complete the processing. Alternatively, if motor processes can be influenced by higher-level processing, this entails that motor processes are not part of a fully encapsulated module. Then, peripheral processing would only refer to processing that requires *less* information from other processes than central processing does.

For the purposes of this thesis, however, the general idea that some processes are open to interference whilst others are not, is very relevant. As the literature review in Chapter 2 shows, there is evidence that word-level processing affects the output process. That can be interpreted as suggesting that peripheral processing is not encapsulated. However, the same evidence cannot tell us if muscular adjustment in the final motor execution is an encapsulated process that relies only on internally available information.

3.3 Parallel and cascaded processing

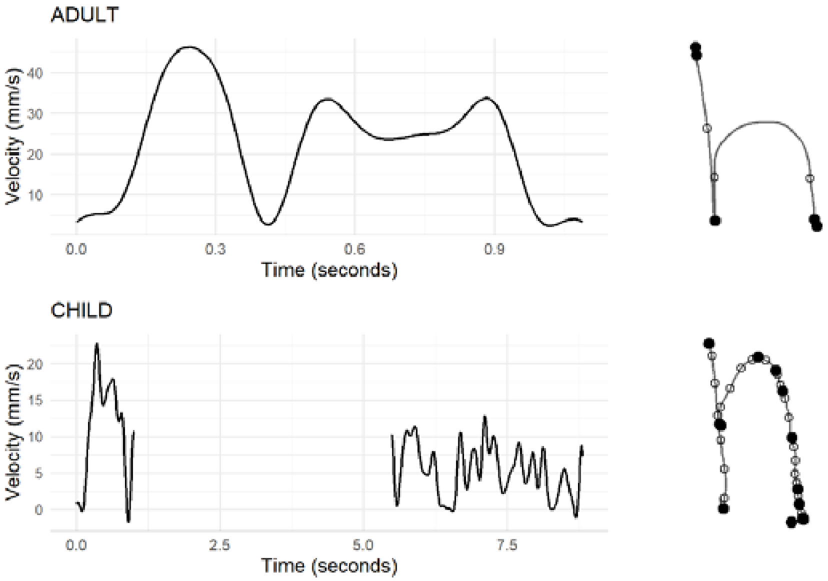
In the opening quote of this chapter, van Galen says that cognitive variables can interfere with real-time production. This is possible only if two or more processing modules are cascaded and their processing takes place in parallel, at the same time. If processing happens in only one module at a time, processing in one module cannot start until the processing in the previous module is fully completed, and processing in the next module cannot begin until that in the first is done. That would be sequential processing (Olive, 2014). In that case, all of the output from one module is sent in one transmission to the next module. In parallel cascaded processing, by contrast, information flows continuously downwards from higher- to lower-level modules without awaiting the completion of processing in any one module.

3.4 Pen-movement fluency

In addition to providing a theoretical framework for explaining the organisation of the processes involved in handwriting, van Galen's work also provides a methodological framework for understanding letter formation above and beyond legibility or in the context of text production. Van Galen et al. (1986) argue that including an analysis of ongoing performance (i.e., pen-movement fluency) can make it possible to determine whether increased processing demands on one or more levels (i.e., higher-level processes) either affects reaction time only or cascades onto motor execution (i.e., lower-level processes). They compare latency and the production process for short (3 letters) and long (5 letters) pseudo-words, finding that latency is longer for long words than for short ones, but also that the third letter in long words reaches a higher peak velocity than the third letter in short words. Hence the processing demands not only affect pre-movement processes but also cascade onto motor execution.

Van Galen et al. (1986) analyse the performance of cursive handwriting letters, which they segment into mainly smooth upstrokes and downstrokes, each of which can be expected to have a single velocity peak. However, Meulenbroek & van Galen (1990) argue that some cursive letters, such as r and z, are motorically more complex than others and that this will cause output to be slower for those letters. In other words, if we assume that increased cognitive demands cascade onto motor execution and slow down the output, simply comparing mean or peak velocities across letters may give the false impression that, say, car is more *cognitively* demanding to write than cat, because the mean velocity of t is higher than that of r. An alternative explanation, of course, is that r is *motorically* more complex than t. Furthermore, Meulenbroek & van Galen (1990) find that letters differ in curvature, and that maximum curvature correlates with their measure of dysfluency. For this reason, the identity of the letters produced must be taken into account in any measure of pen-movement fluency.

Figure 3 *The letter h with velocity profiles*



Note. Speed (tangential velocity) of pen tip, omitting in-air movement, and the final product for an adult and a beginning writer producing lowercase h. Solid circles are locations where the pen was either stationary or lifted. Unfilled circles represent velocity peaks. Velocity is smoothed with a 10 Hz Butterworth filter. Reprinted from Fitjar et al. (2022).

One way of analysing the motor complexity of letters is to count the number of velocity maxima. Whenever the mean velocity of the segment between two data points is higher than that of the segments before and after it, that segment constitutes a local velocity maximum, or a velocity peak. The theoretical maximally fluent production of a straight line requires only one velocity peak, regardless of the length of the line. By contrast, curves require at least two or three velocity peaks, depending on the type of curve (Edelman & Flash, 1987). The difference in velocity profiles between straight lines and curves is evident from the example shown in Figure 3. The adult draws the straight line with a movement requiring only a single velocity peak while the movement to produce the curve requires two velocity peaks. Interestingly, the difference between the adult and the child is more pronounced for the curve than for the straight line.

Counting the number of velocity maxima per segment thus allows comparison of specific samples of real-time handwriting data with the theoretical maximally fluent production of the respective segment, meaning that there is no need to make any assumptions regarding typical human performance. However, in any analysis of real-time handwriting data, there is a need to know what letter the participant wrote. Counts of velocity peaks in the letter L cannot be directly compared with counts of velocity peaks in the letter g because, even though those two letters are each comprised of two features, those two features have different shapes in each letter. In the literature, such features are often referred to as "strokes" (Changizi & Shimojo, 2005; Meulenbroek & van Galen, 1990), probably because adults would typically produce them in a single movement.

If processes operate in parallel and are cascaded, it is reasonable to assume that increased processing demands on a higher level may affect lower-level processing (Lambert & Quémart, 2019). However, first, we do not know if the brain is structured for parallel and cascaded processing from the beginning or whether such a structure emerges with practice. Second, because the lower-level processes typically include allograph selection, we do not know if information is cascaded all the way down to motor execution, or if these final motor processes are somehow protected from higher-level processing such as the retrieval of spelling or allographs.

4 Methods

The method used in each study is described in the corresponding paper. In this chapter, I will first describe and justify the overall design of the thesis. Then I will focus on the individual approaches to data collection and analysis taken in the three studies. I will also discuss some ethical considerations that pertain to studies with vulnerable participants.

4.1 The overall design

The main research question – what are the factors that affect pen-movement fluency when beginning writers form single letters by hand – had to be broken down into three sub-questions. Each of the three studies addressed one sub-question and laid the foundation for the next.

First, unless we are aware of how the characteristics of individual letters affect the measure of pen-movement fluency used, that measure cannot help us to understand how other factors influence production. It is clear from the literature review that the recommended approach is only to compare the production of letters that look the same (Afonso & Álvarez, 2019), but that restricts research opportunities to an extent that may be unnecessary. In Study 1, we explore factors *within the letters* that influence pen-movement fluency. We find that the theoretical maximally fluent production of straight lines and curves differs in the number of velocity peaks. For this reason, we develop a segmentation and coding scheme that describes manuscript letters in terms of straight lines and curves, and we provide criteria for assessing the accuracy of these features. The method based on that scheme allows researchers to compare the letter-formation process across letters and across writers. We illustrate its utility by describing the velocity profiles of 176 children and 27 adults.

Second, with the method developed in Study 1 – which, combined with a simple count of velocity peaks, allows us to compare handwriting kinesthetics across children – we can measure graphomotor performance in various letter-formation tasks. It is clear from the literature review that, for beginning writers, letter formation requires a combination of motor skills and letter knowledge. In other words, children must at first pay attention to what they are going to write and to how they are going to form the corresponding letter, but with practice they develop motor plans for known letters and hence do not need to pay as much attention to motor execution. In Study 2, we explore factors *within the child* that influence pen-movement fluency. More specifically, we focus on pen skills and letter knowledge. The segmentation and coding scheme from Study 1 is used to explore factors that predict within-letter pen movement in various letter-formation tasks. We find that accurate letter formation may mask disfluencies in pen-movement at the beginning of first grade. Further, we find that letter knowledge predicts pen movement in copy tasks after the ability to control the pen as manifested in drawing tasks has been controlled for.

Third, knowing that we can distinguish between motor performance and cognitive aspects of letter formation we decided to use the method to explore how single letter formation is influenced by being in a word. From the literature review we know that writing performance is influenced by word characteristics and letter position (Afonso & Álvarez, 2019). But it is unclear whether the final motor execution is affected, and, in particular, in beginning writers. In study 3 we explore whether pen-movement fluency is influenced when the letter is the first letter in a word, and to what extent word characteristics influences pen-movement fluency in the word initial letter.

4.1.1 Participants

The schools where the participants in the three studies were enrolled had all agreed to participate in the project *DigiHand – the emergence of handwriting skills in digital classrooms* (Gamlem et al., 2020), of which the present PhD project is a part. The DigiHand project recruited a total of 33 schools located on the west coast of Norway, all of which used *Nynorsk* (written Norwegian based on rural dialects) and had more than 10 students per classroom. At urban schools, class size would normally not be an issue, but in rural areas it is not uncommon for there to be fewer students than that in a year and for two or more age groups to be taught together by the same teacher in the same classroom. Because the aim of the DigiHand project is to study handwriting in digital classrooms, the schools differed in the extent to which they used digital devices such as iPads in first grade: 10 of the schools did not have digital devices for each student, and writing instruction in first grade used pen and paper; 11 of them provided each student with a digital device but also taught handwriting in first grade; and 12 of them provided each student with a digital device and postponed handwriting instruction to second grade.

For the present PhD project, I selected 10 classrooms based on whether they taught children to write by hand only (five classrooms) or by keyboarding only (five classrooms) as well as for convenience, to ensure that the research team would be able to visit each school twice within a two-week period for the first round of data collection. The reason for collecting data within such a short period was to enhance internal validity by minimising the maturation effect. As mentioned in Chapter 2.2, many Norwegian schools have implemented a faster pace of letter instruction where children are introduced to two new letters a week. Hence, in theory, the children at the last school we visited could have been introduced to four more letters than those at the first school visited.

Data were collected at two time points – at school entry in first grade and towards the end of first grade – by members of the research team and two trained research assistants.

4.2 Data collection

Data collection at school entry took place during the first two weeks of September (school in Norway usually starts around 16–19 August). Each school received two visits on separate days, one to collect literacy data and one to collect handwriting data. The research assistants, the other members of the research team and I collected literacy data while Vibeke Rønneberg and I collected all the handwriting data for Studies 1 and 2.

Literacy was tested using an iPad while handwriting data were collected by having the children write with an inking ballpoint stylus on an A3-size paper overlayed on a Wacom Intuos digitising tablet. All testing was performed one-on-one with a child and a researcher in a quiet room at the school within normal school hours. Each testing session lasted 20–25 minutes.

Data collection towards the end of first grade was performed during a single session where each child met with me in a quiet room at their school within normal school hours. They wrote single letters and words to dictation on a Wacom Intuos digitising tablet. Each testing session lasted approximately 15–25 minutes, depending on how fast each child wrote.

4.3 Study 1

Study 1 explores how letter characteristics affect a descriptive measure of pen-movement fluency. We ask the following questions:

1. What letter characteristics may influence pen-movement fluency as measured using counts of velocity maxima?
2. How can we measure the fluency and accuracy of single-letter formation?

This is first and foremost a methodological study where the aim is to find a method that (a) allows us to distinguish between different combinations of fluent/disfluent and accurate/inaccurate letter production as shown in Figure 4 and (b) enables us to compare production across letters and across writers.

Figure 4 *Possible combinations of fluency and accuracy in letter production*

Fluent and accurate	Fluent and inaccurate
Disfluent and accurate	Disfluent and inaccurate

Some of the data used for Study 1 were those collected for the purposes of Study 2 – which could not be analysed for those purposes until an appropriate method had been developed. The child sample comprised 176 children from the 10 first-grade classrooms described in Section 4.1.1 and the data were collected, as mentioned above, during the first two weeks of September. In addition to the child sample, 27 adults who were faculty and other staff at a Norwegian university were recruited using convenience sampling.

4.3.1 Handwriting data

The children and adults alike copied letters and letter-like symbols Ø[7] Ω A ǂ M d Ψ h T ɣ e ゐ g R, see appendix 3 actual stimuli. The first items two were test items, which were not submitted for analysis. All participants were asked to write with their dominant hand. The adults were afterwards asked to complete the task with their non-dominant hand. The stimuli were displayed on cards presented one at a time by the researcher and the participant copied them within pre-printed 2.5-cm square boxes.

To mimic the children's typical writing environment, all participants wrote with an inking ballpoint stylus on regular A3-size printer paper. See Appendix 3 for a filled-out test sheet used in Studies 1 and 2. Hence they were able to see what they wrote on the sheet of paper rather than

[7] Ø is a letter in the Norwegian alphabet

on the monitor of a laptop computer. The children usually wrote with pencils and were normally not allowed to write with ball-point or fountain pens at school. While beginner pencils are often thicker to make them easier to grip, we were limited to using the slimmer inking stylus to capture pen-movement data. This may of course have affected performance, but at least all participants wrote with the same stylus.

In writing tests in other studies it varies whether the test paper has pre-printed lines or not. I chose to ask the participants to write within these boxes because that would provide the writer with some support. The size of the box would indicate the maximum letter size, but otherwise not restrict the child. Younger writers (6-year-olds) have been found to produce more legible letters with unlined paper while 9-year-olds benefitted from lines with regards to legibility (Lindsay & McLennan, 1983). Because the children in this sample are inexperienced writers, we chose to not provide lined paper.

4.3.2 Segmentation and coding scheme

Based on theoretical claims about the required number of velocity peaks in straight lines and curves, respectively (Edelman & Flash, 1987; Marquardt & Mai, 1994), we described manuscript letters in terms of the number of straight lines and curves that were separated by necessary discontinuities (Changizi & Shimojo, 2005). For example, the letter A has three straight lines, and the letter d has a straight line and a curve. These are referred to as “letter parts”. Following this logic, we broke down all the upper- and lower-case letters of the English alphabet to ensure that the logic can be applied to all letters in the alphabet. This allowed us to identify the same letter parts in letters written by the children in our sample. However, three straight lines do not always make an A – size and relative position matter as well. In fact, three straight lines can also make an H. For this reason, we also specified criteria for “letter features” for each letter. A letter feature is a letter part plus criteria for size, shape and position. All features are coded independently of how they were produced. Pen traces that are not part of any letter feature are coded either as connecting strokes or as extras, such as false starts. For the purpose of Studies 1 and 2 we applied the same logic to the four letter-like characters ǂ Ψ ɣ ゐ and described them in terms of letter features as well. Thus, we could compare the straight lines and curves regardless of whether it was part of a letter or a letter-like character.

In short, the letter A consists of three letter features. Feature A1 is straight and diagonally oriented, similar in length to A2, slants top to right and meets A2 at the top to create an acute angle. Feature A2 is straight and diagonally oriented, similar in length to A1, slants top to left and meets A1 at the top to create an acute angle. Feature A3 is straight and horizontally oriented, must be long enough to meet or slightly overlap A1 and A2, and must be placed at the middle of A1 and A2. For ease of reading, all of this information (and corresponding information for all other letters) is given in a table in the appendix to Paper 1.

To measure pen-movement fluency, we used OpenHandWrite (Simpson et al., 2021) to collect time-course data. We calculated the mean velocity between every pair of data points (every 7.5 ms). Whenever the mean velocity of a segment between two data points was higher than that of the segments before and after it, this was deemed to constitute a local velocity maximum, or a velocity peak. To remove measurement noise, we then filtered the velocity time-course using a 10Hz fourth-order low-pass Butterworth filter. Such filtering of raw data yields a smoother velocity profile, because some peaks are removed. The stronger the filter, the fewer velocity peaks remain. Unlike a stronger 5 Hz filter, a 10 Hz filter is supposed to remove measurement noise only while keeping peaks pertaining to motor activity.

Such a filtered velocity profile combined with a descriptive measure of pen-movement fluency based on a simple count of velocity peaks yields a direct measurement of graphomotor performance that can be used to explore factors that influence the letter-formation process.

4.4 Study 2

The aim of Study 2 is to explore child-level factors that affect pen-movement fluency in single letters. More precisely, we seek to establish to what extent pen control (i.e., the fine motor skills required to control pen movements) and measures of various dimensions of letter knowledge might explain individual children's ability to fluently draw letters, either by copying or from memory.

In kindergarten, visuomotor skills are associated with letter copying (Marr et al., 2001; Weil et al., 1994), while handwriting accuracy is associated with letter and word naming (Molfese et al., 2011). In older children, spelling ability is associated with neatness in letter formation (Caravolas et al., 2020). The domain-general graphomotor skill (i.e., the skill used to reproduce mental representations of various figures on the page – not limited to known letters) and letter knowledge are both associated with the ability to produce accurate letters in copy tasks. On a different note, Pagliarini et al. (2017) argue that Italian children in first grade, like the older children in their experiment where letter size and speed were manipulated, adhere to the principle of homothety (i.e., keeping relative letter durations constant) and to the principle of isochrony (i.e., keeping movements proportionally related to trajectory length. This indicates that when children start writing letters to dictation, they use movements similar to those in skilled writers.

We are interested in children's ability to move the pen without the added load of letter writing, and in children's letter knowledge without the load of forming letters. To compare how children write letters they might know with how they write unfamiliar letters, we need to measure their letter-formation ability (fluency and accuracy) both regarding letters they might be familiar with and regarding unknown letters (or letter-like symbols). Letter formation in a copy task may require different skills than letter formation in a dictation task. In the copy task, the child can rely solely on visuomotor ability. By contrast, the dictation task requires the ability to map phonemes to graphemes. Studying performance on a copy task with regard to both letters and symbols makes it possible to isolate the effects specifically associated with retrieving a letter form from memory (which may happen in the case of letters but not in that of other symbols).

We address two questions: In children at the beginning stages of learning to write…

3. To what extent do factors associated with pen-control and with letter knowledge affect pen-tip movement fluency in copied letters and symbols?
4. After control for letter-copying ability, to what extent do factors associated with letter knowledge affect fluency when forming letters from dictation (i.e., in response to hearing letter sounds)?

4.4.1 Method

We report data from children (N = 176) who had recently started first grade. We measure the children's motor ability, their letter knowledge and their letter-formation ability. To limit the burden on the children, the testing was split across two sessions.

To explore factors affect graphomotor ability, we measure the children's ability to move the pen. We asked them to draw with an inking ballpoint stylus on an A3-size test sheet printed on regular paper. The tasks were administered in order of increasing resemblance to writing, starting with straight lines and circles, then upward and downward garlands with continuous movements, and finally figure eights. See Appendix 3 for a filled-out test sheet. The tasks were adapted from Gerth et al. (2016). We measure disfluency in performance on these tasks with the Signal-to-

Noise velocity peaks difference (SNvpd), developed and described by Danna et al. (2013).

Letter knowledge is measured using tasks that differ in whether graphemes are included. Two tasks – phoneme isolation and phoneme blending – measure phonological awareness. The other two tasks – encoding and decoding – measure phoneme–grapheme knowledge. The tasks were selected from a battery of tests previously administered to Norwegian first-graders (Lundetræ et al., 2017; Solheim et al., 2017, 2018).

The ability to form letters is measured using the same copy task described in Section 4.3.1. We asked the children to copy four lower-case letters, four upper-case letters and four letter-like symbols in the following order: A ǂ M d Ψ h T ɣ e ゐ g R. The purpose of including the letter-like symbols is to provide a baseline measure of letter-writing fluency in cases where the children write letters that they have never practised writing or have even never seen before. To familiarise the children with the task they first copied to test-items Ø Ω. These were not submitted for analysis.

The ability to write single letters is measured using a dictation task where the children had letter sounds presented to them and were asked to write the corresponding letter. The letter sounds they heard were /l/, /f/, /i/, /b/, /o/, /p/, /u/, /s/, /k/ and /v/. These letters were selected because the motor plans associated with the upper- and lower-case versions of them are comparable. The children wrote these letters within pre-printed 2.5-cm square boxes.

We marked up letter features and coded them for accuracy in accordance with the segmentation and coding manual developed in Study 1. Raw time-course data were filtered using a 10 Hz fourth-order low-pass Butterworth filter in OpenHandWrite (Simpson et al., 2021) to remove measurement noise. The measure of letter-production fluency is based on the number of velocity maxima per letter feature.

4.4.2 Analysis

We examined how character-writing fluency is influenced by measures of pen control and literacy skills by comparing a series of nested linear mixed-effects models with random by-item (character) and by-child intercepts (Baayen et al., 2008) using the Lme4 R package (Bates et al., 2015). In our data, we had multiple observations both per child and per character. Observations are therefore nested within both child and character, which must be considered when analysing the data. In Study 1, we demonstrated that different letters require a different minimum number of velocity peaks. Because the letter L can have as few as two velocity peaks while the letter M must have at least four, it is highly likely that the average number of peaks per letter will differ between them. In the regression model, we address this by adding random by-item intercepts. By setting each character with their own intercept or starting point in the regression model, we assume that there is a typical pen-movement fluency associated with each allograph, but this varies across allographs. Similarly, each child produced several letters, and we can assume that each child has a unique combination of skills that makes up their "letter-writing ability". By setting each child with an individual intercept, we assume that each child has a typical ability to produce letters fluently, but that this varies across children.

4.5 Study 3

The aim of Study 3 is to explore to what extent pen-movement fluency is affected by lexical processing when writers who are in the early stages of learning how to form letters and words write single words to dictation.

There is evidence to suggest that when adults handwrite or type single words to dictation, some of the processing of the word takes place before the first key or pen press while the rest of the processing takes place afterwards (Hess et al., 2020; Kandel et al., 2013). Such continuous preparation manifests itself in longer inter-letter intervals (Álvarez et al., 2009) or longer stroke durations (Hess et al., 2018).

Evidence from studies of children's single-word writing suggests that low-frequency words are associated with a longer writing-onset latency (Afonso et al., 2018; Kandel & Perret, 2015) and – in particular for younger writers (in second grade) – with longer writing durations (Afonso et al., 2018). However, Kandel & Perret (2015) argue that lexical characteristics do not affect motor execution until children are older. If so, the above findings would suggest that allograph retrieval has been completed before the first pen press but that the spelling of the word has not necessarily been fully retrieved at that point. This is in line with studies of spelling accuracy, where low-frequency or long words have been found to be more prone to spelling errors (Søvik et al., 1996).

In our research, we are interested in how pen-movement fluency in the word-initial letter is affected by word frequency or word length. A detailed analysis of pen movement in the word-initial letters and the associated writing-onset latency will reveal whether or not the allograph is fully retrieved before the first pen press. By including the ability to write single letters to dictation, we want to isolate the effects of writing words, regardless of their lexical characteristics. In other words, we want to explore the children's underlying ability to fluently produce single letters, without the additional effort required to spell any word.

We address two questions:

5. To what extent do characteristics of the word to be produced (length and frequency) affect processing time prior to output onset?
6. To what extent, if at all, do length and frequency affect graphomotor performance (i.e., the fluency of pen movement) for the first letter once output has been initiated?

4.5.1 Method

We report data from children (N = 88) towards the end of first grade who had been taught to write by hand.

We first measure their ability to produce single letters without the added load of spelling and then as the word initial letter in a word controlled for length or frequency. The words are four word-pairs controlled for frequency with length held constant, and four word-triplets controlled for graphemic length with frequency held constant. All words within a pair or triplet start with the same two letters. All words can be correctly spelled using the sub-lexical route. Words that are difficult to spell because they include consonant clusters or diphthongs were avoided.

Selecting the words to be included in the pairs and triplets turned out to be a challenging task. There is no official list of high- and low-frequency words in children's Norwegian. One option considered was to use a list of 1600 words with information about the self-reported age of acquisition for each word (Lind et al., 2015), but we considered that age of acquisition would not necessarily indicate how familiar children were with the written form of a word at the age of six. We also had access to a corpus of German words used in children's literature (Schroeder et al., 2014), but given that some words would have several possible Norwegian translations, it would be difficult to argue that the translation chosen in such cases had a similar frequency in Norwegian as the original German word. In the end, we selected words from the Norwegian Newspaper Corpus that were similar in frequency and are commonly used in Norwegian daily speech and are not inappropriate to use around children[8].

[8] It can be noted that the word *porno* 'porn' was a better fit in terms of frequency than *potet* 'potato', but the former is clearly not appropriate to ask six-year-olds to write in a spelling task (and may also be more common in newspaper texts than in the speech of first-graders).

We measure their pen-movement fluency in single letters with a letter-to-dictation task. The letters were chosen because they are either the first or the second letter of the words in the spelling-to-dictation task. The letter sounds were played through an external speaker connected to the laptop. The letter sounds were played once and the children were asked to write down the letter they heard, either upper- or lower-case. They were then asked to write it once more in the same style before they were asked to write it twice again in the opposite casing. The presentation of the letter sounds was randomised. If the child produced the wrong letter at the first attempt, I would demonstrate writing the correct letter and the child then wrote the correct letter twice as upper-case and twice as lower-case.

We measure their pen-movement fluency in word initial letter with a spelling-to-dictation task. The children wrote 20 words to dictation. The children first heard a sentence: "Mor les ei bok" ("*Mother reads a book*") and were then prompted to write: "Skriv 'bok'" ("*Write 'book'*"). The prompts were played through an external speaker connected to the laptop. The children wrote on A4 sheets of paper secured to the Wacom Intuos Pro large tablet. The paper had lines as we assumed that children were now accustomed to writing on lined paper. See appendix 5 for an example of the test sheet completed by a participant.

We marked up the all the letters produced by the children and coded each letter as either upper-case or lower-case as well as for accuracy in accordance with the letter descriptions included in the segmentation and coding tool from Study 1. Because we compare production across children but not across different letters, we only identified letters, not letter features. However, because some children had been taught different letter forms[9], we did sometimes identify several allographs of the same letter. The letters produced were matched with the target word

[9] Some children produced letters that were ready to be joined with a little curved flick at the end, such as *d* rather than d and *a* rather than ɑ.

and we calculated Levenshtein's distance, which is a measure of how many edits separate two words. For example, the Levenshtein's distance between *put* and *cut* is one, because one letter must be edited to turn one into the other. This distance was then converted into a ratio, given that the words differed in graphemic length. For each letter, we calculated the tangential velocity at each sample point. The raw data were filtered using a 10 Hz fourth-order low-pass Butterworth filter in the Signal package (Ligges, 2014) in RStudio in order to remove measurement noise. We also measured onset latency, which is the time between the beginning of the spoken stimulus and first pen press.

4.5.2 Analyses

Like the data in study two, data comprised observations of fluency and accuracy for the single letter or word initial letter of different words written by each child. Again, we have multiple observations for each letter (single and in different words) and for each child. Therefore, when we examine how word characteristics affect character writing fluency, we compare sequences of nested linear mixed effect models (e.g., Baayen et al., 2008) using the Lme4 R package (Bates et al., 2015). The analysis of difference between single letters and word initial letters had random intercepts for each child in the first model while random intercepts for letters were introduced in a later model. The analysis of word initial letter production had random intercepts for each child.

4.6 Ethical considerations

The project was reviewed and approved by the Norwegian Centre for Research Data as part of the DigiHand project (Gamlem et al., 2020). Written informed consent to participate in all studies was provided by the participants' legal guardian or next of kin.

According to the Norwegian national ethical guidelines for the social sciences and humanities (NESH, 2021), children have an individual right to refuse participation in research projects. All children were invited to participate and could refuse participation on the day of data collection.

Participation in the project is voluntary for all schools (principals), teachers and children. First, principals were contacted and asked whether they would be interested in participating in the project after we had carefully selected the schools based on strict criteria. Without support from the principal, we would not move forward with a school. Although the principal would not be involved in the project, we needed their endorsement to ensure that we were welcome and that the teachers would have the support required to remain in the project for two years. The teachers were also asked for consent; concretely, the principal was asked to forward the information to the relevant teachers. Further, all schools in the area concerned usually organise a meeting for parents of new first-graders approximately three months before school starts in August. Two researchers were present at each of these meetings, presenting the project to the parents and asking for their consent. To avoid delay and confusion when data were collected for the first time, it was important to ensure that all those who wanted to participate in the project had signed the consent form before the summer vacation. There is a fine line between encouraging people to participate and exerting undue pressure – especially peer pressure – on them to do so. For reasons of research quality, we need as many as possible to say yes, but we also have to be explicit about the right to say no. Hence it was important to explain to the parents that the tasks would not cause any stress or discomfort to their children.

Children are considered a vulnerable group. Parental consent is required to include them in research projects. However, even where a child's parents had signed the consent form, making us legally entitled to make the child perform the tasks, it would have been morally wrong to force a child to complete a task. The guidelines are explicit on this subject:

> At the same time, it is important to treat minors as independent individuals. According to the Children Act, a child who has reached seven years of age, or younger children who are able to form their own opinions on a matter, must be provided with information and the opportunity to express their opinions (NESH, 2016:21)

The children in this project were between five and six years old at the time of the first round of data collection. We would introduce ourselves in the morning and tell them that we were interested in how children write just as they are starting school. We said that they would perform some tasks on an iPad, and we showed them the sheet of paper that they would be writing on during the second day. Most children were excited to participate and expressed joy and enthusiasm. A few were more reluctant at first, but when they saw the tasks, they all seemed content in the end. In one case, a child had a change of heart before the tasks started. That child was allowed to go back to the classroom. I asked the child again later that same day if they wanted to have a go. They said yes and completed the tasks successfully. During the second round of data collection, we encountered a different case. A child had been struck from our records, based on a note saying that they had withdrawn since the time of the first round of data collection, carried out at school entry. However, when that child was told that they would not be allowed to perform the tasks, they started crying. The teacher called the parents to ask if the child could participate after all. The parents gave their permission orally, and everything worked out fine. However, these two examples illustrate that we should listen even to young children. Parental consent is important, and in our case it was necessary for another reason as well, namely because we asked the parents to fill out a questionnaire providing background information about the child and the home situation.

Rhodes (2010) questions the concept of voluntary consent. She argues that informed consent does not necessarily lead to morally sound research. If I interpret her arguments correctly, it is the responsibility of the researcher to design a morally sound study, for which participants can sign up. Hence we need to cultivate a research environment that promotes full disclosure as well as trust between researchers and participants. However, this touches upon a difficult topic in all research: that of biased samples. If some individuals are denied the right to participate in a study, by the researcher or by a guardian acting on their behalf, the samples may become biased. In educational studies, one likely reason for refusing to let one's child participate might be that "my child is not able to complete the tasks and will feel bad afterwards". From the parents' point of view, this makes perfect sense, as most parents will do everything in their power to protect their child. However, if all children who did not know many letters when entering school were to be excluded from the study, the data would be biased, and the results of the analyses would be less trustworthy. Knowing that the tasks I asked the children to complete would not cause them unreasonable stress or discomfort and having research assistants with years of experience working with children in similar situations, I feel confident that it was a correct choice to invite the reluctant student back in and to call the parents of the one who really wanted to participate, so that both of them could participate.

5 Summary of findings

The main research question in this thesis is what influences pen-movement fluency when beginning writers write single letters. This question was explored from three different perspectives: factors within the letter, factors within the child and factors within the lexical context. Each question was further narrowed down into two specific research questions. In the following sections I will briefly summarise the findings.

5.1 Factors within the letter

In the first study we ask whether there are factors within the letter that influence pen-movement fluency.

1. What letter characteristics may influence pen-movement fluency as measured using counts of velocity maxima?
2. How can we measure the fluency and accuracy of single letter formation?

We argue that the theoretical maximally fluent production of a straight line requires one velocity maximum (or peak) whereas that of a curve requires two or three.

By breaking down manuscript-style letters into straight and curved features with criteria for accurate production, we can assess and describe pen-movement fluency and the accuracy of individual features. We describe a segmentation and coding scheme to show how we did this.

We illustrate how the segmentation and coding scheme can be applied by describing the velocity profiles of children (N = 176 first grade students) and adults (N = 27) performing a letter-copying task. The child sample is the same as in study 2. An additional purpose of this was to investigate whether our theoretical assumptions were valid, which we found them to be.

We find that when adults produce straight features, the most typical number of velocity peaks is one. When they produce curved features, the most typical number of velocity peaks is two. Both of these findings apply regardless of whether they use their dominant or non-dominant hand, albeit with some more variation when the non-dominant hand is involved. Most features are produced accurately by adults. By contrast, the children produce the same features less accurately and with a larger number of velocity peaks for both straight and curved features. In general, less accurate features are produced less fluently.

To summarise, we find that characteristics within letters that may influence pen-movement fluency are whether features are straight or curved and whether features are produced accurately or not.

5.2 Factors within the child

In this study we explore if there are factors within the child that may influence pen-movement fluency in single-letter formation, we focus on the children's ability to control the pen and on their letter knowledge, asking the following questions: In children at the beginning stages of learning to write…

3. To what extent do factors associated with pen-control and with letter knowledge affect pen-tip movement fluency in copied letters and symbols?
4. After control for letter-copying ability, to what extent do factors associated with letter knowledge affect fluency when forming letters from dictation (i.e., in response to hearing letter sounds)?

For the research question 3 we find that the simple pen-control measures – straight lines and circles – do not predict copy fluency. By contrast, the more complex pen-control measures – continuous garlands and figure eights – do predict copy fluency. This suggests that pen-movement ability in non-letter handwriting tasks depends on what is produced, and only the more complex tasks predict handwriting performance. Phoneme-to-grapheme encoding ability predicts pen-movement fluency in copying both letters and letter-like symbols. Children who were familiar with a wider range of letters manifested a more fluent production not only of potentially known letters but also of unknown letters, here represented by letter-like symbols. Further, malformed features were produced less fluently than correctly formed features.

For research question 4, we find that there was an apparent difference between straight and curved features in the dictation task. Specifically, fluency in curved features was predicted only by copying fluency regarding both letters and symbols, whereas fluency in straight features was also explained by letter knowledge. In the dictation task as well, malformed features were produced less fluently than correctly formed features.

To summarise, there are factors within the child that influence pen-movement fluency. Those factors pertain both to motor skills and to letter knowledge. Children's ability to move the pen intentionally when copying figures is not the same as their ability to move the pen intentionally in order to copy letters, because then the scores on the different tasks would have correlated perfectly. Thus, there appears to be a development from being able to move the pen in a controlled manner in order to make either a straight or a circular movement, which almost all children are able to do at school entry, to being able to see a figure, hold an abstract representation of it in one's mind, create a motor plan and then move the pen with smooth movements to execute that plan, something that fewer children are able to do at school entry.

Letter knowledge predicted fluency in both letters and letter-like symbols in the copy task. In the dictation task, letter knowledge was associated with better fluency in straight features but not with better fluency in curved features. It thus appears as though general letter knowledge mostly affects copying ability. Whereas in the dictation task the child must have an abstract allograph representation in mind, then a more general knowledge of other letters is less important. This suggests that there is a fundamental difference between copy and dictation tasks and that they tap into different skills.

5.3 Factors within the lexical context

In the third study we focus on factors within the lexical context that may influence pen-movement fluency in the writing of the initial letter of words. We ask the following questions:

5. To what extent do characteristics of the word to be produced (length and frequency) affect processing time prior to output onset?
6. To what extent, if at all, do length and frequency affect graphomotor performance (i.e., the fluency of pen movement) for the first letter once output has been initiated?

We were surprised to find that single letters were produced less fluently than word-initial letters, meaning that single letters do not represent an underlying and untainted ability for letter formation.

There was no effect of frequency or length on either writing-onset latency or pen-movement fluency. We did, however, find effects of both frequency and length on spelling accuracy. Specifically, high-frequency words were spelt correctly more often than low-frequency words, and short words were spelt correctly more often than medium-length or long words.

Our interpretation is that when beginning writers – within a semi-transparent orthography – hear a word, they identify the first allograph, retrieve the associated motor plan and then start writing the letter without processing the rest of the spelling. For beginning writers letter formation may still be a task that requires deliberate and active thinking and is therefore processed centrally rather than peripherally.

6 Discussion of factors that affect letter-level pen-movement fluency

In the introduction I argued that we need to know more about factors that contribute to pen-movement fluency when beginning writers form single letters because it is a prerequisite for handwriting, and it is linked to their ability to produce text. Through these three studies I have explored how factors within the letter, the child and the word affect pen-movement fluency when beginning writers form single letters. In this chapter, I will discuss the knowledge produced in the three studies, first separately and then in light of the main research question.

6.1 The letter

Rooted in theory about and computational models of human movements needed to produce straight lines and curves, we propose a coding and segmentation scheme for manuscript letters where letters are segmented into sub-letter features with criteria to determine if the feature is accurately produced. Kinesthetics of letter features that are spatially similar can be compared across children. We argue that features must be identified without reference to how they were produced, but that they must be coded for accuracy to ensure a like-for-like comparison. The count of velocity peaks per feature is then a measurement of graphomotor performance that does not include time when the pen is stationary (on paper) or in the air. We illustrate the scheme in use by describing velocity profiles of letters copied by adults and children. Most importantly, we find that whether features are straight or curved, and whether features are produced accurately or not may influence pen-movement fluency.

In van Galen's model (1991), motor execution for real-time trajectory formation is the final step in handwritten production. Where van Galen in his earlier work explored variation in up- and downstrokes in cursive handwriting, (Meulenbroek & van Galen, 1986, 1990), we have adapted this approach to work manuscript style letters. We defined similar letter parts in manuscript letters and suggested criteria for what would be reasonable accurate production.

Whereas cursive handwriting is typically produced with continuous movements, manuscript letters are discrete units (Meulenbroek & van Galen, 1986). It makes sense to segment the real-time trajectory formation of cursive handwriting based on kinematic characteristics to separate the different letters in a word. Furthermore, movements are hard to omit in cursive handwriting. The discrete nature of movements in manuscript letters requires the writer to produce each letter as a full package, but with multiple movements. In literature letter strokes are used to refer to both the movement and the trajectory formed by the movement. In other words, the movement motivates the segment. We propose that the pre-defined segment should motivate the movement. By defining the segment, we can then describe and compare the movement.

The finding that the adult sample produced straight lines typically with one velocity maximum is in line with Marquardt et al. (1999: 226) who argue that "smooth and single-peaked velocity profiles reveal that the ongoing movement was neither aborted nor disturbed". They find that adults produce the straightish lines used in cursive version of "ll" with a single-peaked velocity profile. This also supports our argument that straight lines do not need to be perfectly straight. The feature can have some curvature and still be produced with one velocity peak. Unlike the curved segments described by Edelman & Flash (1987). They argue that there are four basic stroke types in cursive handwriting: hook, cup, gamma and oval. In brief, hook and cup are both open simple curves while gamma is a closed complex and oval is closed simple curve. The difference between a simple and a complex curve is whether the trajectory crosses itself at any point. They argue that the oval requires three velocity peaks while the others only require two. Our findings suggest that curved features require two velocity peaks. However, the handwriting sample in studies 1 and 2 were not designed to explore the difference between open and closed curves (e.g., the difference between the u and o, or between a d produced with either closed or open curve). Future research is recommended to explore this further.

In terms of accuracy of shape, size and position of features we defined criteria based on the Minnesota Handwriting test (Reisman, 1993). The criteria provided in the MHT to assess legibility is based on absolute measures because the test requires children to attempt to produce letters of a certain size. Our attempt at converting these absolute measurements to relative ones resulted in our rule of $1/6^{th}$ of letter height. We decided that this was how much a letter feature could deviate from the prototypical letter feature and still be recognised as that letter feature. This is exploratory work and needs further validation.

One strength of the segmentation and coding scheme is the combination of a rigorous and systematic approach with the flexibility it offers researchers. When the scheme is applied rigorously, researchers will obtain a good overview of all the pen traces produced by the child in the attempt to form a given letter. Nevertheless, its simplicity makes it flexible. For example, letters are made up of straight lines and curves. Curves can be broken down into open and closed ones, and it is for the individual researchers to decide whether to make that distinction given their research purpose. In Study 3, we decided that, for the purposes of that study, there was no need for feature-level information, given that no attempt was made to compare across letters. We did, however, use the scheme to ensure the allographs were comparable. On that note, in our sample, there was no reason to distinguish between upper-case and lower-case versions of the letter V, as both V and v are comprised of two straight lines and a theoretical maximally fluent production of each has two velocity peaks. However, researchers may add additional allographs using the very simple logic of straight lines and curves. Furthermore, researchers can decide whether connecting strokes should be submitted to analysis. Additional variables, such as stroke direction, pen pressure or pen tilt, can also be either calculated or extracted from software. To summarise, there are many possibilities – all of which require researchers to make deliberate decisions about what to include and what to ignore.

However, there are also some weaknesses to this scheme. At present, the marking-up of letters must be performed manually, which is a time-consuming task with a high risk of miscoding. For this reason, data cleaning is of the utmost importance. Still, with a sample of, say, 170+ children producing 20 letters with approximately three features each, the data set will be massive. We found it helpful to plot the letters from the data set to ensure that the features were correctly marked up and tagged. Even so, future research should investigate how this process can be automated.

Overall, we believe that the segmentation and coding scheme in combination with a fluency measure (e.g., counts of velocity peaks) can provide a meaningful measure of graphomotor performance also in beginning writers.

6.2 The child

In short, we find that the more complex pen-control tasks as well as phoneme-grapheme encoding ability predict copy fluency in both copied letters and symbols. After letter-copying ability is statistically controlled for, phoneme–grapheme encoding ability predicts fluency in straight features when children write letters to dictation.

In the paper, we suggest that the ability to draw straight lines and circles reflects eye–hand co-ordination skill. Drawing continuous garlands and figure eights also requires a child to make a mental representation (after the movement has been presented to the child) and reproduce it on paper. The basic tasks – straight lines and circles – both had ceiling effects, meaning that almost all children could produce those movements fluently. These are the movements that Mai & Marquardt (1994) referred to as stroke patients' preserved potential for automated movements. While the stroke patients in question had lost the ability to produce letters fluently, the children in this study had developed the underlying movement skills but had yet to develop fluent letter-formation movements. Even so, this can be interpreted as evidence that children at school entry in Norway have already developed the ability to move the pen intentionally and fluently in simple movements that require little by way of visuomotor skills. However, the more complex tasks – the garlands and figure eight – require additional eye–hand co-ordination, including the ability to move the hand to make the garlands or to have lines cross each other and also change direction to make the figure eight. Unless every new loop is meticulously copied, the child must also keep an abstract representation of the garland in mind while performing the task. In a way, this might be interpreted to mean that these tasks require some of the same skills that are used to produce letters from an abstract representation. Since the focus of my research is on pen-movement fluency in letter formation, we did not collect extensive amounts of data on the children's pen movements in other tasks, but we did find that the children produced curved features less fluently than straight features. This might be interpreted to mean that curves are more challenging to produce because they require changes in curvature (Morasso & Mussa Ivaldi, 1982). In terms of visuomotor control, what a person drawing a straight line must determine is length and direction; for a curved line, curvature must also be taken into account. As a consequence, these tasks make direct demands on domain-general graphomotor skills. The limited data that we do present in the paper, however, suggest that the exploration of pen-movement fluency and accuracy in non-letter writing or drawing tasks might shed new light on these pre-writing skills.

The findings also suggest that the real-time trajectory formation is affected by children's general letter knowledge. Letter knowledge predicts pen-movement fluency in the copy task, both for letters and for letter-like symbols that the children had not previously been exposed to. In other words, higher-level processing cascades onto motor execution when children copy single letters. This indicates that a lack of letter knowledge directly interferes with production, as production is constantly monitored (Glover, 2004) or motor execution is processed centrally, with the child constantly making decisions about the direction of the trajectory. This would not be the case if allographs had been selected and completely retrieved prior to the first pen press. Alternatively, the fact that phoneme-to-grapheme encoding ability also predicts fluency in letter-like symbols suggests that a good visuo-spatial ability is a precursor to learning phoneme–grapheme correspondence. This is confirmed by other studies exploring the relationship between handwriting and visuomotor skills in kindergarten children aged 5 to 6 years (van Hartingsveldt et al., 2015).

As argued above, when children form letters disfluently, the underlying cause may be weak graphomotor ability with emphasis on their visuomotor skills. However, we also find that their general abstract letter knowledge influence pen-movement fluency. In other words, beginning writers use higher-level information about phoneme – grapheme connections when they deliberately and intentionally activate central processes to form letters accurately. That letter formation is an active task in beginning writers is in line with previous research on the relationship between central and peripheral processing when beginning writers copy text, (e.g., Afonso et al., 2018).

One limitation of this study is that we did not investigate direct relationships between levels of performance regarding single letters in the different tasks: phoneme-to-grapheme, grapheme-to-phoneme, phoneme segmentation, phoneme blending, copying and writing to dictation. Hence, we do not know, for example, whether the child who produced the letter h fluently in the copy task also recognised it in the phoneme-to-grapheme task or was able to segment out the h sound in a spoken word. This is linked to an alternative explanation for the findings made, namely that children who have practised forming letters may, as a consequence, have developed their abstract letter knowledge (Bara & Bonneton-Botté, 2018; Longcamp et al., 2008).

Another limitation is that we did not include any background information about the children. We do not know, for example, who spent their time drawing and who spent their time climbing trees before starting school. We do not know who has been read to and has been included in literacy events at home and at the *barnehage*. Indeed, instead of carrying out the studies described in this thesis, we could have set out to identify early predictors of letter-formation ability related to environmental factors. However, rather than looking backwards, we wanted to assess some of the children’s motor skills and some of their literacy knowledge at the point of school entry. This allows us to identify and then talk about what children – in general – *can* do when they start first grade in Norway, not what we wish they *could* do.

Our study is only a first attempt at including both process and product measures when identifying factors within the child that contribute to letter forming abilities. Hence, it would be premature to draw conclusions regarding implications for instruction based on this study. However, future research should pay attention to pen-movement fluency in combination with performance on visuomotor tasks and various letter-formation and writing tasks. The fact that our findings are in line with previous research shows that the method we have developed to better understand children's letter formation is valid.

6.3 The lexical context

In short, we were surprised to find that single letters are produced less fluently than word-initial letters and that there is no effect of frequency or length on either writing-onset latency or pen-movement fluency. We did, however, find effects of both frequency and length on spelling accuracy.

First, we were surprised to find single letters were produced less fluently than word-initial letters as the reason for including single letters were to determine the children's untainted ability to form letters. The literature review showed that there is consensus that some words are more difficult to spell correctly (Søvik et al., 1996) or take longer to write (Lambert et al., 2011). If some words are more difficult than others, simply writing words to dictation should also require more processing than writing letters to dictation. Second, we find that the motor execution of the word initial letter is not affected by lexical characteristics of the target words. Because fluency in word initial letter is better than in single letter writing, we argue that the motor processes are not informationally encapsulated and that there is no such thing as a basic ability to form letters. However, it seems most likely that when the children start forming the word-initial letter, the first allograph has been fully retrieved but the processing of the next sound has not yet started. This can be seen to support the idea that beginning writers process word writing sequentially.

It may be the case that this explanation is valid only with regard to a semi-transparent orthography, or at least only with regard to words that can be accurately spelt through phoneme-by-phoneme assembly. As discussed in chapter 2.5, orthography may influence spelling strategies. In syllabic languages like Spanish, writers tend to treat syllables as units (Álvarez et al., 2009). Further, there is reason to believe that this is a consequence of writing instruction. As discussed in Chapter 2.2, beginning reading and writing instruction in Norway is dominated by the phonic approach. Within this tradition children are explicitly taught to sound out each letter, step by step. The word spelling strategy may therefore possibly be explained by teaching efforts. This finding can therefore not be generalised to other types of orthographies and writing instruction.

The main analysis is limited to word-onset latency and to the fluency of the word-initial letter. Letter-formation accuracy and spelling accuracy are included because we need the full picture. In fact, considering either product or process data will yield only part of the truth, meaning that both must be considered.

One limitation to this study is that we only included words we that we assumed the children would be able to spell correctly using the sub-lexical strategy that they are most likely are taught at school. Hence there were no potential spelling conflicts that needed to be handled. If we had included words giving rise to such conflicts, that would have added another dimension besides length and frequency. Because we also find an effect of length and frequency on spelling accuracy, we can say with some confidence that the words used in the experiment did influence the writing process.

As discussed in Chapter 4.5.1, determining the frequency of words to use in the experiment was less than optimal as we had to resort to using a newspaper corpus. In the literature I have read while working with this thesis, frequency is rarely discussed. Baayen et al. (2016) problematise the concept of frequency in studies of lexical processing in light of linguistic contexts, different corpora, and the individual vs collective experiences. In Study 3, high frequency words are words that we expect children to be familiar with, both semantically and in their written form. However, we do not know to what extent they had practiced writing these words. An idea for future research is to design an experiment where we could compare production in words the children practiced writing by hand repeatedly with words the children had only practiced typing or reading. This could bring new knowledge about whether handwritten performance is influenced by frequent graphomotor experience or by lexical processing.

Another limitation to this study is that we only evaluated how the word characteristics influenced the pen-movement fluency of the word initial letter. It is plausible that any effect of lexical characteristics would materialise later in the writing process. Roux et al. (2013) suggest that hesitation might be more likely later in the word, while Kandel & Perret

(2015) argue it is more likely either towards the beginning or towards the end of the word. Future research should explore the remainder of the writing process, using both pen-on-paper measures and pen-in-the-air measures.

6.4 Factors that influence pen-movement fluency in single letters

In short, we find that pen-movement fluency in single letter formation appear to be supported by general letter knowledge at school entry and the lexical context at the end of first grade. Furthermore, curved letter features are produced less fluently than straight features, and malformed features are produced less fluently than accurate ones. When beginning writers write the first letter in a word, pen-movement is more fluent than when the letter is all alone. Fluency in letter production in beginning writers depends both on their visuomotor skills and their letter knowledge. Most importantly though, the ability to form letters with a fluent movement is more than the ability to move the pen in a controlled manner. All in all, the findings suggest that motor execution is influenced by the fact that the child produces letters, due to the shape and probably construction of the letters and due to the motor and higher-level processing involved in letter production.

7 Theoretical reflections and implications

This thesis provides new understanding about pen-movement first graders form letters. In this chapter I will discuss how the findings also provide support for the theoretical framework presented in Chapter 3, van Galen's model of the writing process. Based on the knowledge produced in this thesis, and albeit we have not explicitly studied how children learn to form letters by hand and use that skill for handwriting, I believe the work in this thesis provides a good foundation for some educated guesses and speculations about instruction in handwriting. If nothing else, offers some ideas for future research.

The premise for the studies in this thesis is the belief that higher-level processing can influence lower-level processes, and the real-time trajectory formation is the lowest possible process. In that regard, the findings from the studies in this thesis might suggest that processing on the allograph level in the model by van Galen (1991) cascades and therefore influences pen-movement fluency when beginning writers copy letters, but processing on the spelling level does not influence pen-movement fluency in the word initial letter. This may be interpreted as support for the argument that processing at this particular point – in children's writing development and/ or within the word – happens in parallel. However, without further analysis of the performance in the remaining letters it is impossible to say whether spelling in general is processed in parallel and spelling of the entire word is performed phoneme-by-phoneme.

In van Galen's model, allograph selection is considered the highest level of graphomotor processing according to Lambert & Quémart (2019). While spelling is assumed to be processed centrally, it appears that allograph selection may either be processed centrally or peripherally.

Wing (2000) argued that letters are stored as abstract movements and that the writer can execute the plan with any limb. When the adults in our sample produced letters with almost as good fluency and accuracy with their non-dominant hand as their dominant hand, this may be interpreted as support for Wing's argument that adults have motor plans for letters that are not dependent on the effector. The idea that each allograph is associated with a motor plan are further used to support the argument that children need to practice writing letters by hand in order to learn an establish motor plans for each letter (Mangen & Velay, 2010). However, the fact that children who score high on the phoneme–grapheme test also produce unknown letter-like symbols with a high degree of fluency may be interpreted as if children used their knowledge about letters to create motor plans on the fly for these unknown letters. In the copy task when they copied unknown letter-like symbols it would be impossible for them to recall a motor plan for the entire letter. What they potentially could recall, however, was a motor plan for letter parts and a general knowledge of how to connect two letter parts. Therefore, one plausible explanation is that letter formation in beginning writers is part of a broader learning process where the child learns to make sense of the little drawings that we call letters. It seems that learning the letters is not just about learning specific letters, but also about learning how the alphabetic system works, and what constitutes a letter and what does not.

The fact that pen-movement fluency in copied letters at school entry is influenced by how many letters the child is familiar with suggests that learning to write letters is not just about learning to write specific letters and remembering their exact representations. One explanation is that the children who have learnt letters, without formal instruction, have probably also learnt how to discriminate between the letters. Traditionally, it has been recommended to introduce letters that are easily confused, such as b and d, separately (Graham et al., 2000). It might however be beneficial for children who have not yet discovered that letter characteristics like directionality matter if a teacher teaches this skill explicitly. However, these are mere speculations, but maybe we should ask what we are not teaching children today and thus find new ways to teach and support children who do not "catch" writing.

8 Conclusion

This thesis explores handwritten letters, produced by beginning writers, and factors that might affect the production. I developed a tool that allows researchers to explore both the end-product (accuracy) and process (fluency). We apply this tool in our work with letters written by children in first grade, at the early stages of learning how to form letters and words.

The knowledge produced in this thesis pertain both to methodology and theory about processes in handwriting. Methodologically, the contribution to the field of writing research is that it is possible and meaningful to assess pen-movement fluency of letter formation in beginning writers. However, we must consider both product and process when we research writing. We find that when we manipulate a task, the effect may be evident in both product and process or only in product or only process. Theoretically, the contribution is that even beginning writers show traces of parallel cascading processing when they form letters by hand, but also that there is a difference between writing single letters and writing letters in word. This last issue should however be explored further.

9 References

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Paper 1

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Assessing handwriting: a method for detailed analysis of letter-formation accuracy and fluency

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Abstract

Educationally-oriented measures of handwriting fluency – tasks such as written alphabet recall and sentence copying – conflate graphomotor skill and various higher-level abilities. Direct measurement of pen control when forming letters requires analysis of pen-tip velocity associated with the production of sub-letter features that, in a skilled handwriter, are typically produced in a single, smooth movement. We provide a segmentation and coding scheme that identifies these features in manuscript letters and gives criteria for whether or not a feature is accurately formed. We demonstrate that, in skilled handwriters, these features are the product of smooth movements: The velocity profiles of adult writers (N = 27 performing a letter-copying task) producing straight-line features and curved features gave modal velocity-peak counts of 1 and 2 respectively. We then illustrate the utility of our segmentation and coding scheme by describing the velocity profiles of beginning writers (176 first grade students with minimal handwriting training). This sample produced the same features with less accuracy and with a substantially greater number of velocity peaks. Inaccurate features tended to be produced more slowly and less fluently.

Keywords Handwriting · Assessment · Fluency · Accuracy

Introduction

Handwriting is now relatively rare as a means of communication for most adults. However, it remains the dominant writing modality in the vast majority of primary school classrooms. Developing the ability to produce neat, or at least legible, handwriting is therefore important. Handwriting neatness affects subjective

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ratings of text quality. Studies in which raters assess compositional quality of texts that are neatly or untidily written but are otherwise identical or matched have consistently found that lower, and often substantially lower, ratings are given to the untidy texts (Bull & Stevens, 1979; Chase, 1979; Klein & Taub, 2005, review by Graham et al., 2011). In the majority of educational settings untidy writing will result in teacher criticism. Danna et al. (2016) describe a vicious cycle in which criticism reduces self-esteem which results in handwriting avoidance, which again results in reduced opportunity to improve.

Developing handwriting automaticity is also important. As might be expected, the fluency with which children are able to form letters on the page affects their productivity when composing text (Berninger et al., 1997; Graham et al., 2000), and there is some evidence that it also affects the quality of the resulting composition (Alves et al., 2016). Handwriting ability is, therefore, needed not just for the production of aesthetically pleasing text. It is, in most educational contexts, a necessary precursor to effective written communication.

Researchers exploring handwritten production therefore need tools that allow assessment both of the written product – the neatness or at least accuracy with which letters are formed on the page – and also of the fluency with which the pen moves across the page when these letters are produced. Although accuracy and fluency are likely to be correlated, particularly in young children, developing an understanding of the writing process requires that these are assessed independently: Real-time handwriting data need to be analysed in such a way as to be able to distinguish not just fluent, neat writers from inaccurate disfluent writers, but also writers who are fluent but inaccurate, and those who are disfluent but accurate.

Our aim in the present paper is to describe and illustrate one such tool. We first review existing research-focussed approaches to handwriting assessment. We then give a detailed description of the approach that we have adopted in our own research. By segmenting the handwriting trace into sub-letter features this approach makes possible fine-grained analysis of writers' ability to control their pen movements. In the final section of the paper, we illustrate the use of the tool with a comparison of children and adults forming single letters.

Research-focussed approaches to handwriting assessment

A range of tools have been developed to meet the needs of researchers and educators in identifying children whose handwriting is unusually poor and therefore requires remediation (see Feder & Majnemer, 2003 and Rosenblum & Weiss, 2006 for reviews). Most of these include measures of both the neatness of the handwritten product – the form of the pen-trace as it appears on the page – and a measure of rate or fluency of the process by which this is produced. In practice, these are inseparable. Product accuracy must be interpreted with reference to how fluently the text was produced, and vice versa. For ease of explanation, however, we will first discuss approaches to product assessment, and then approaches to measuring process.

Assessing the handwritten product

Tools for assessing the handwritten product can be described broadly as either holistic or analytic. Holistic assessment involves raters making a global judgement about the legibility (readability) of a handwriting sample. Ayres (1912) described a legibility measure based on how long it takes to read a text, averaging across several readers. Much more recently Larsen and Hammill (1989) developed the Test of Legible Handwriting based on matching handwriting samples to benchmark exemplars representing different levels of reading ease and neatness. Other measures elicit holistic ratings of legibility or of characteristics that are assumed to impact legibility. The Children's Handwriting Evaluation Scale (Phelps & Stempel, 1988) rates samples for form, spacing and general appearance. The Handwriting Legibility scale (Barnett et al., 2018) scores texts for legibility and effort-to-read, and raters also provide a single, global score for how well letters are formed, defined as containing all necessary elements, i.e., having appropriate shape, being neatly closed, and being consistent in size and tilt. Several other similar tools exist (e.g., Amundson, 1995; Molfese et al., 2011; Ziviani & Watson-Will, 1998).

Analytic approaches, by contrast, aim at direct measurement, on a letter-by-letter basis, of the degree to which a letter confirms to a neatly-written ideal. Helwig et al., (1976); see also Collins et al. (1980); Jones et al. (1977) described an approach to establishing accuracy when a writer is required to precisely copy model letters. Children copy letters onto paper with four guidelines: a baseline, upper and lower lines to guide maximum and minimum vertical extent, and a midline above the baseline. Inaccuracies are identified, using transparent overlays, where letter components deviate from the model by more than a set tolerance (1, 2 or 3 mm depending on researcher purpose). This provides a binary copying-accuracy measure for each sub-letter unit (is accurate or is not accurate, separately for, for example, the straight line and the curve in a lowercase *h*).

The strength of this approach, for research contexts, is that in contrast with holistic measures, it provides very precise diagnosis of which features a writer is not able to form precisely. The pen-control deficit of a child who, for example, struggles to keep letter height within bounds is potentially quite different from the deficit associated with producing malformed curves. The disadvantage, however, is that it necessarily requires precise copying not just of the form of a presented letter, but also its dimensions. This provides an overly-specific definition of what constitutes an accurately formed letter, both in terms of form – there is no possibility for variation in allograph – and in size.

The widely used Minnesota Handwriting Test (MHT; Reisman, 1993) also scores a sample of text on a letter-by-letter basis. However, unlike the transparent-overlay method, the sample text is a sentence that participants copy without the requirement to exactly reproduce letter form. In the manuscript version participants are, however, required to print rather than use cursive script to write within three guidelines. For each letter, scorers first determine whether or not it is possible to identify the letter out of context. If the letter passes this test, then it is given a binary score for form (for example whether gaps or overlaps within the letter are all less than 1.6 mm), for position relative to the printed baseline (must be within 1.6 mm), for size (all letter components must be positioned correctly relative to guidelines), and for letter and word spacing. Each legible letter is therefore given a score out of 5 representing its neatness.

The approach adopted by the MHT in scoring letter form is conceptually different from that implemented by the transparent-overlay method. The transparent-overlay method specifies a specific form for each letter, whereas the MHT applies the same neatness criteria across all letters. If the researcher requires by-child neatness scores – and this is the aim of the MHT – then this makes sense. However, if researchers need to know whether a specific letter was formed well, as might be the case for example in an experimental context, then letter-specific form criteria are required. The transparent-overlay method is one way to provide these. It is possible, however, to specify form individually for each letter without constraining size and allowing at least some flexibility in allograph choice. For example, the "criteria for letter formation" provided by Ziviani and Elkins (1984, Table II) specify necessary (but not sufficient) characteristics for each letter. For example, a lowercase *m* must comprise a "double smooth curve finishing on aligned base".

Assessing production fluency

Handwriting fluency measures are, broadly, of two different types, delineated by implicit assumptions about the range of processes that are encompassed by the term "handwriting". Educationally-focussed research that, for example, explores the effects of handwriting ability on the quality of children's written compositions (e.g., Abbott & Berninger, 1993; Kim & Schatschneider, 2017; Limpo & Alves, 2013; review by Kent & Wanzek, 2016), tends to use tasks that capture a range of skills over-and-above the motor planning and execution necessary to form a letter. All of the studies reviewed by Kent and Wanzek measure fluency by recording the number of characters children wrote in a fixed period of time when recalling the alphabet or when copying a written sentence or paragraph. Both the MHT and the Detailed Assessment of Speed of Handwriting (Barnett et al., 2009), for example, involve copying an unfamiliar sentence that includes all of the letters in the English alphabet (although necessarily with unrepresentative letter and digraph frequencies). Rate of output when performing this task will depend upon motor planning ability and pen control. However, it will also require reading, short-term memory, attention, and orthographic retrieval.

More direct measures of the speed and fluency with which a writer can form known letters – i.e., of those components of the handwriting process that are directly related to planning and controlling pen movement – can be captured by participants writing on a digitising tablet (or, at lower resolution, with a smart pen). This permits a broad range of measures that describe how the pen moves across that page (see review by Danna et al., 2013). At minimum, measuring pen movement, unlike measures that just count characters produced in a fixed period, differentiates between time spent with the pen moving on the page and time spent with the pen lifted or stationary (e.g., Paz-Villagrán et al., 2014; Sumner et al., 2013). Pen lifts or stops will, for

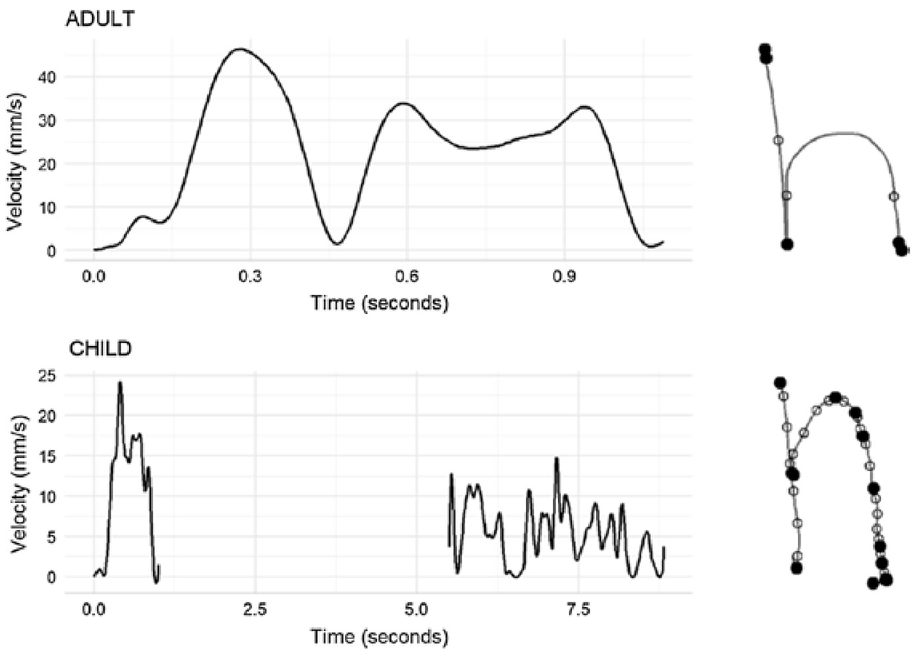

Fig. 1 Speed (tangential velocity) of pen tip, omitting in-air movement, and the final product for an adult and a beginning writer producing lowercase *h*. Solid circles are locations where the pen was either stationary or lifted. Unfilled circles represent velocity peaks. Velocity is smoothed with a 10 Hz Butterworth filter

example, occur (probably) in sentence copying tasks when the writer is reading the next words to be copied (probably, but see Alamargot et al., 2007).

Measuring pen movement also permits a direct measure of mean pen-tip speed (Khalid et al., 2010; Kushki et al., 2011; Rosenblum et al., 2006; van Galen et al., 1993). For example, van Galen et al. found that 2nd to 4th graders identified by their teachers as having untidy handwriting moved the pen more quickly than peers. Kushki et al. (2011) found that 4th graders showed decreasing vertical velocity but increasing horizontal velocity as they progressed through composing a paragraph. Most obviously, competent adult writers show much faster mean pen-movement speed than beginning writers (writing single words: adults around 80 mm/s, Hepp-Reymond et al., 2009; 6-year-olds, around 10 mm/s, Séraphin-Thibon et al., 2019).

Underlying this variation in speed is the extent to which letter components are formed with smooth single movements. This is illustrated in Fig. 1, which shows the velocity profile and final product for a competent adult producing a lower-case letter *h*. The upright is formed in a single, ballistic movement. The velocity curve for this feature – the first peak in the speed plot – is smooth, formed by a single acceleration and deceleration. Contrast this with the much less fluent velocity profile for the corresponding feature produced by a child in the lower panel. Whilst the adult produced this feature in a little over 300 ms, the child took over three times longer. This difference in speed and fluency is even more marked in the formation of the curved feature of the *h*.

A range of indices have been suggested for measuring pen-tip movement disfluency (Broderick et al., 2009; Khalid et al., 2010; Rosenblum et al., 2006; Smits-Engelsman & Van Galen, 1997). One relatively straightforward approach is to smooth the velocity trace to some extent, as is the case in Fig. 1, and then simply count the number of times that velocity reaches a local maximum (a *velocity peak*; e.g., Overvelde & Hulstijn, 2011). Average velocity and velocity peak-count are strongly correlated, at least in beginning writers (Fitjar et al., 2021), but velocity peaks are causally prior to slow production: The child in Fig. 1 produced the two components of the *h* much more slowly than the adult *because* their pen accelerated and decelerated multiple times.

Two other characteristics of the velocity profiles shown in Fig. 1 are important to note. First, the disfluency in the child's pen movement was particularly marked when producing the curve. This is to be expected. The motor planning associated with forming a straight line has two degrees of freedom – length and direction. Curves add the need to manage angular change. This adds considerable complexity to both planning and execution (see Morasso & Mussa Ivaldi, 1982, for a computational model and Habas & Cabanis, 2008, for fMRI evidence). Séraphin-Thibon et al. (2019) found that pseudowords composed of letters that contained more curves were written with a larger number of velocity peaks than otherwise-matched pseudowords with fewer curves.

Second, maximal fluency does not mean zero velocity peaks. Drawing a straight line necessarily involves starting and finishing with the pen stationary and so, at minimum, there must be one velocity maximum between these two points. This is the case for the adult writer in Fig. 1. Similar constraints apply to curved features: Edelman and Flash (1987) showed that both open and closed loops (hook, cup and gamma strokes, in their terminology) necessarily involve two velocity peaks, yet are still produced with maximum fluency. This again can be seen in the adult's formation of the curve (inverted cup) of the *h*.

Product segmentation for process analysis

Determining the extent to which a specific sample of real-time handwriting data represent fluent production involves, therefore, making a comparison between the velocity profile for the sample and the theoretical maximally-fluent velocity profile for the production of the same text. One approximation to this is simply to make comparisons between groups who have, a priori, been identified as poor or good handwriters on the basis of the neatness of their handwriting (e.g., Di Brina et al., 2008; Rosenblum & Werner, 2006; van Galen et al., 1993). It is also possible to make a priori assumptions about differences in the bandwidth of velocity spikes that constitute disfluency and those that are an essential to fluent production (Danna et al., 2013; Meulenbroek & van Galen, 1986). Danna et al., for example, counted velocity peaks after low-pass filtering of pen-tip speed at 10 Hz (as in Fig. 1) and then subtracted a count of velocity peaks after low-pass filtering at 5 Hz on the grounds that the latter were likely to be a necessary characteristic of competent, fluent production. This permits estimates of pen-movement fluency across extended text.

A more fine-grained approach is to segment letters into standard features that in competent, fluent writers could be produced as a single stroke – i.e. as a pen movement bounded by points where the pen-tip is stationary or near-stationary and / or lifted (e.g., Meulenbroek & van Galen, 1990). These features then provide a basic unit of analysis when comparing pen movement across writers or experimental conditions. This is the approach that we have taken in our discussion of the fluency of production of the letter *h* shown in Fig. 1. By segmenting the letter *h* into two features – a straight line and a curve – it was possible to make direct comparison between the adult and child samples.

For an approach based on marking up pen traces into features to be an effective research tool it needs to meet the following criteria:

First, and most obviously, it must be universally applicable: The segment delineation for a specific letter must be applicable across a wide range of different attempts at forming that letter by different writers.

Second, segmentation must be possible on the basis of the written product, without reference to information about how the letter was formed. Automatic segmentation based on process – dividing up letters into components based on units that are composed in single strokes – is possible, of course (see, for example Rosenblum et al., 2006). However, this will identify different segments depending on whether a letter is produced fluently or disfluently. The reason for this can be clearly seen in Fig. 1 by considering the different location of the pen stops and lifts in the adult and child letters. If the purpose of segmenting the letter is to then establish the fluency with which the segments are produced, then the procedure by which segmentation is achieved must itself be independent of fluency.

Third, because there is potential for a trade-off between speed and precision, the segmentation procedure also needs to take some account of the accuracy with which a segment is formed. To compare like-with-like it is necessary to know whether a feature is well shaped and positioned.

Finally, the segmentation procedure must allow for the possibility of variation in allograph. Again, this is illustrated in Fig. 1. Although we have been talking as though the curved component of the *h* is comparable across the adult and child samples this is, arguably, not the case: In the classification used by Edelman and Flash (1987), the adult forms a cup whereas the child forms a hook. The production demands of these two features may well be different. Segmentation must therefore differentiate between various allographs that represent the same letter but comprise different features. In practice this means that common allographs of the same letter will require their own segment codes, but obviously also that the coding scheme must identify these different allographs as representations of the same letter.

The coding scheme that is the focus of this paper aims to meet these criteria. We describe a formal, though we believe intuitive, schema for segmenting Latin lower and uppercase letters into sub-letter features, and for then determining whether or not the feature is formed and positioned with adequate precision. This develops the "criteria for letter formation" (Ziviani & Elkins, 1984) approach to coding the handwritten trace into a rigorous formalism for segmenting letters into sub-letter units that can then be directly compared in terms of kinematics of their production. In the next section of this paper, we give a detailed description of our letter-segmentation and coding scheme. In the final section we provide evidence for its value in comparing production fluency across writers.

A scheme for letter segmentation and accuracy coding

Our coding scheme specifies, for each letter, a set of rules that (a) segments letters into sub-letter features, based on the shape of the pen trace, (b) provides criteria for deciding whether or not the feature is well formed. These are illustrated, for upper case *R*, in Table 1 and given in full in the appendix. The descriptions in the appendix describe common allographs of both upper- and lower-case printed letters. This is intended as illustrative rather than definitive and should be adapted by researchers to suit local context and their research needs.

Segmentation

Our strategy for identifying sub-letter features within a particular writer's output depends just on the pen trace – the shape that the writer forms – and does not make reference to how the writer produced the feature. A feature is identified if it corresponds, within specified tolerances, to a feature as defined in our coding scheme (see example in Table 1). However, decisions about what constitutes a feature in a prototypical letter form – the decision, for example, to identify 3 distinct features in *R is* process-based. In developing the coding scheme, we identified features in a letter as the minimum number of components in an allograph such that, in maximally-fluent handwriting, each feature could be produced with a smooth velocity profile and without the pen either stopping or lifting (i.e., as a single pen stroke). Under this definition the letter *C* comprises a single feature, *T* comprises two features, *N* comprises three features, and so forth. Features may be either straight, as is the case for both features in *T,* or curved, as in feature R3 of *R* (see Table 1).

Marking up a specific pen trace into segments – identifying feature boundaries – is, as we have said, independent of the process by which that trace was produced. So, although in a skilled writer a feature will normally start and end with a pen stop or lift, this information is not used when deciding for a particular pen trace where a feature starts and ends. We defined features based on the spatial characteristics of acceptable letter forms – i.e., how the letter appears on the page – and then look for pen trace segments that, alone or combined, match these characteristics. As we discussed above, identifying features independently of how they were produced allows comparison of the kinematics of production of the same features across writers with varying graphomotor ability.

We use MarkWrite v 0.4.9 (Simpson et al., 2021) to segment and code handwriting traces. MarkWrite takes as input data captured in real time from a digitising tablet or, at lower resolution, a smart pen. It requires just that data provide, at minimum, time and coordinates for each pen-location sample. The MarkWrite interface is illustrated in Fig. 2. Sequences of samples that comprise a feature, as defined by

Table 1 Example of coding scheme with specifications for size and position of each feature

Feature code		Shape and orientation	Size	Position
R1		Straight, vertical	Length is twice the width of the curve in feature 2	To the left of features 2 and 3
R2_1		Curve, open	Width is half the length of feature 1, Length: shorter or similar to height of feature 1	To the right of Feature 1 Open end towards feature 1 Top arm meets with top of feature 1 and bottom arm meets feature 1 in the middle
R2_2		Curve, closed	Width: half the length of feature 1 Length: shorter or similar to height of feature 1	To the right of feature 1 In the upper half of feature 1
R3		Straight, diagonal	Shorter than feature 1	To the right of R1 Slant bottom to right Meets lower arm of feature 2 and or middle of feature 1

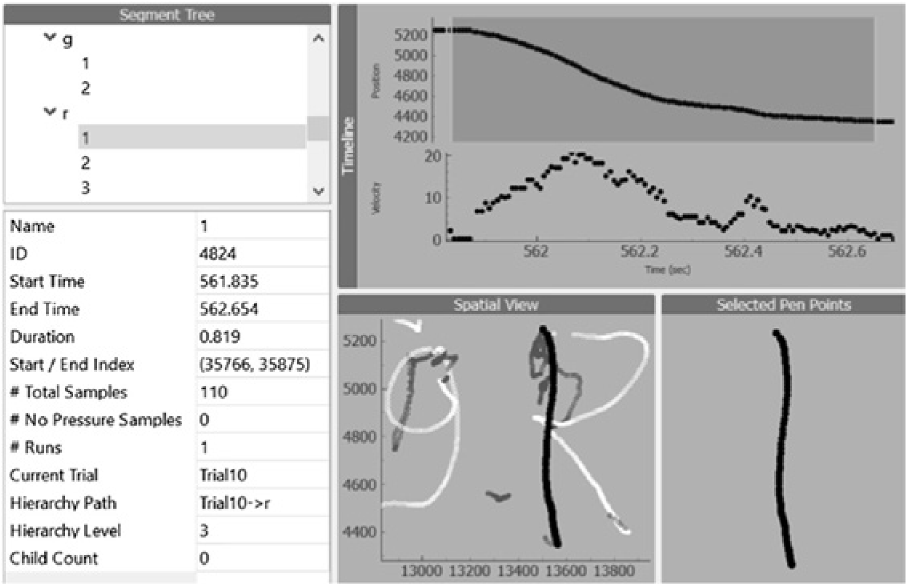

Fig. 2 Screenshot from the MarkWrite program showing selection Feature R1 from a child's copying an uppercase *R*. The upper right panel shows change in y-axis location (upper plot) and pen-tip speed (lower plot) over the period when this feature was produced. The black trace in the spatial view is a selected set of samples that represent a single feature (annotated as R1). The grey trace represents in-air movements

the coding scheme, are selected either by cursor movement or by keyboard shortcut. Then the feature is annotated with a feature label and, if it is inaccurate, one or more codes to indicate how it deviates from well-formed.

Accuracy

Once features are identified, the coding scheme then allows a binary decision about whether or not a handwritten feature was produced accurately. By accurately, we mean the extent to which the pen-trace corresponds to an acceptable representation of the target feature with regards to shape, size and position. In our coding, this decision is made without regard to aesthetics – we define relatively broad criteria for acceptable feature representation – and as with segmenting into features, accuracy coding is agnostic about the kinematics of the feature's production. Decisions about accuracy (and / or neatness) criteria will depend on research purposes. The criteria we present here are illustrative rather than prescriptive. In our own implementation we applied a general tolerance of 1/6 of letter or feature height or width in determining whether or not features deviated from the shape, proportion or size defined by their allograph. This corresponds approximately to the 1.5 mm tolerance on 9.5 mm ruled paper allowed by the Minnesota Handwriting Test (Reisman, 1993). Our approach differs from the MHT, however, in that we allowed for variation in absolute letter size, and therefore applied proportional rather than absolute tolerance criteria.

In Fig. 3 we illustrate six versions of the letter *R,* all of which have at least one inaccurate feature.

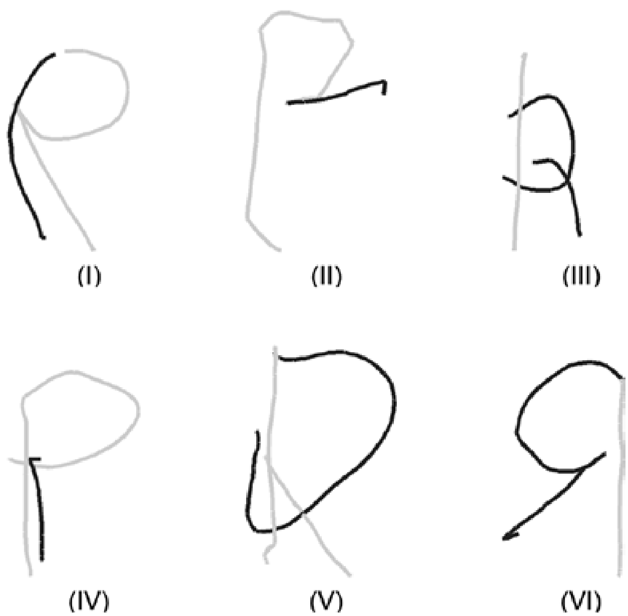

Fig. 3 Different inaccurate versions of the letter *R*

Shape

Shape accuracy depends on the straightness for straight features and curvedness for curved features. Decisions about straightness were made relative to the feature's length and without reference to other features in the letter. The rule is that the feature is coded as inaccurate if the pen trace deviates from the straightest path between the ends of the feature with more than 1/6 of the feature length. In Fig. 3 the first *R* (I), the feature R1 (highlighted in solid black) is inaccurately shaped. Curvedness requires the pen trace to deviate from the straightest path between endpoints with more than 1/6 of feature width without the trajectory crossing itself. Thus, the feature length (measured between endpoints and bottom of the curve) must be at least 1/6 of feature width (measured between the two most extreme points to each side of the endpoints). All the curved features in Fig. 3 are sufficiently curved. In our data, lack of curvedness was generally not a problem.

As shown in Table 1, curves can be either open or closed. Open curves need an opening that is at least 1/6 of feature width. Closed curves can have a gap or overlap between endpoints that corresponds to 1/6 of feature width. For letters with only one option, such as U, a gap smaller than 1/6 of feature width means that the letter is not accurately shaped. Likewise, the letter O can only be written with a closed curve and a gap larger than 1/6 means the letter is not accurately shaped.[1] For letters with options, such as R2 in Table 1, this distinction has two purposes. First, it makes letter description easier. Second, this is a scheme intended for exploring handwriting fluency and we recognise that other researchers may have an interest in curved features in particular. Although we have not pursued this further at the moment, other researchers might find this useful.

Position

Positioning of features refers to spatial orientation of features as well as gaps and overlaps between features. For open curves spatial orientation refers to the direction of the open end – left, right, upwards and downwards – and is described for each letter. Straight lines can be either vertical, diagonal or horisontal. In this coding scheme, the tolerances for gaps/overlaps are 1/6 of letter height, or feature height in case of curves. In Fig. 3, the top arm of the R2 feature of R (III) does not meet the top of R1 as specified in the table. The horizontal overlap is within the 1/6 tolerance for overlap between features that should meet. The vertical overlap exceeds the 1/6 tolerance and is coded as inaccurate for position. The R3 feature in the same letter does not meet R2 and is therefore coded as inaccurate for position. The R3 in R(IV) and R(II) are not diagonal, slanting bottom to right, and are therefore coded as

[1] In copy and letter to dictation tasks it is clear what the target letter is. If the child saw or heard /u/ and produced a curve with a 1/6 gap between endpoints, then it is the letter u. If the scheme is applied to spelling words to dictation or free composition tasks researchers will need to make some additional decisions about letter interpretation.

inaccurate for position. The R2 and R3 in R(VI) are both inaccurately positioned as both are placed to the left of R1.

Size

For a feature to be accurate it also needs to meet relative size criteria. Criteria for size are letter specific. These are described in Appendix 1. To illustrate, in the letter *R* the vertical straight feature must be proportional to the other two features and vice versa. The rule is that the length of R1 is twice the width of the curve in R2. The length of the curve, R2, must be shorter or similar to length of R1, and the width must half the length of R1. Unless specified the tolerance for size difference is 1/6 of the previously produced feature. In Fig. 3, the curved feature R2_1 in the R(V) is too big in comparison with the previously produced feature, as the width of the curve is almost the same as the length of R1.

Alternative allographs

All letters have several legal allographs, depending on whether it is an upper-case or lower-case, block or cursive version. In addition, some letters have several allographs within these categories. As Fig. 4 shows, the upper-case *A* is an example of a letter with two allographs; one has two straight features slanting towards each other at the top while in the other the straight features are replaced by one curved feature. The scheme is open-ended and may need to be adapted and augmented in specific contexts.

One feature – multiple segments

A feature may be produced with a single stroke (e.g., the *h* open curve – feature h2 in our coding scheme – produced by the adult in Fig. 1). A feature can also be produced with multiple pen-stops as is the case for the child's production of the *h* open curve in Fig. 1. It may be produced in two or more distinct movements. The bar of the *T* – feature T2 in our coding scheme – would typically be produced by a skilled writer in a single stroke. Figure 5 shows this feature, T2, being produced, by a beginning writer, in two distinct movements. The numbers represent the sequence in which these were generated, and arrows indicate approximate initial direction of pen trajectory. The movement is separated by a pen lift and in-air move, and with the pen moving in different directions to produce each segment. It is not even the case that a feature must be produced with consecutive movements as illustrated with

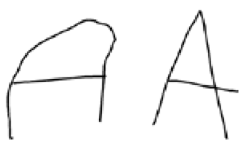

Fig. 4 Two handwritten allographs for the letter *A*, one has one curved and one straight feature and the other has three straight features

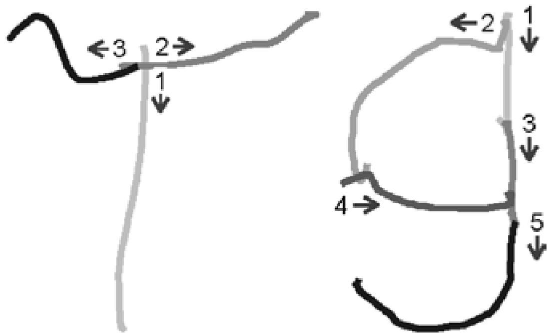

Fig. 5 Handwritten letters in which features are produced with multiple actions. Different line shades represent pen traces bounded by pen lifts. Numbers represent the sequence in which these were generated. Arrows indicate approximate initial direction of pen trajectory. The feature g1, for example, was, therefore, produced in three separate non-consecutive movements – segments 1, 3 and 5. Data are digitally-sampled pen movements by a Norwegian child who was just starting to learn how to handwrite

the *g* in Fig. 5. The feature g1 – in our coding scheme – is produced in three distinct and non-consecutive movements.

Handwriting fluency in adults and beginning handwriters

Our purpose in this section is to illustrate how the segment and coding scheme can be used as the basis for a detailed analysis of the kinematics of single letter production in a sample of very early writers, and of competent adults.

Participants and task

Our child sample comprised 176 Norwegian children tested within the first four weeks of first grade (mean age 6.2 years, 86 girls). Early childhood care and education in Norway (*Barnehage* / Kindergarten) is attended by 97.6% of 5 year olds (Norwegian Directorate for Education & Training, 2019).[2] Children in kindergarten do not, however, follow a set curriculum and, in particular there is no requirement to learn handwriting before the start of primary (elementary) school. Many of the children in our sample were, therefore, at the very start of learning how to handwrite. Our adult sample comprised faculty and other staff at a Norwegian university ($N=27$, 23 women). We did not record age.

Both children and adults copied the letters A M d h T d g R. Letters were displayed on cards presented one-at-a-time by a researcher.[3] Participants copied these within pre-printed 2.5 cm square boxes. They were instructed to "write the letter as they saw it", without a requirement to exactly copy its form.

[2] 92.8% of all children between 1 and 5 years old attend *Barnehage* (SSB, 2021).

[3] As part of the same task participants also copied 4 unfamiliar letter-like symbols. We do not report data from these or the two practice items – one letter and one symbol – in this paper.

All participants were asked to write with their dominant hand. Adults then completed the task again, writing with their non-dominant hand. This provided a direct motor-control manipulation, holding all other factors that might affect production fluency constant.

Participants wrote with an inking ballpoint stylus on paper overlayed on a Wacom Intuos XL digitising tablet connected to an HP Elitebook i5 laptop. Pen-tip locations were sampled at intervals of around 7.5 ms (133 Hz) and with a spatial resolution of at least 330 lines/cm. Software for pen-movement capture and analysis was provided by the OpenHandWrite suite of programs (Simpson et al., 2021) which provide a digitising tablet interface for PsychoPy (Peirce et al., 2019).

Data from the child sample are a subset of data previously reported in Fitjar et al., (2021), although the analyses reported in this paper are new. Adults were sampled specifically for this paper.

Processing handwritten data

Pen traces were segmented and coded according to the segmentation and coding scheme presented in the previous section. If copied accurately, using most-common allographs, these 8 letters segment into a total of 20 features. We additionally classified these as either straight or curved. The motor plan for producing a curved line is more complex than a straight line and these different motor plans are reflected in different kinematic profiles (Habas & Cabanis, 2008; Morasso & Mussa Ivaldi, 1982). This means that the effects of graphomotor difficulty, in writers with impaired or not-yet-developed graphomotor ability, are more likely to be exhibited when drawing curves than when drawing straight lines (e.g., Fitjar et al., 2021). The letters for the present task – reproduced with the most common allograph, gave 8 curved and 12 straight features.

The digitised pen traces were first segmented into features, with boundaries at the first visible (non-zero pressure) sample that was part of the pen-trace associated with an identifiable feature. We then calculated tangential velocity (speed) of the pen tip at each sample point and then filtered the resulting velocity timecourse with a 10 Hz 4th order low-pass Butterworth filter. The 10 Hz filter removes measurement noise. We then counted remaining velocity maxima for each feature (see, for example, Khalid et al., 2010; Overvelde & Hulstijn, 2011; Smits-Engelsman et al., 2001).

Results

We present analysis of these data as follows: We describe the distribution of velocity maxima for straight and curved features produced by adults writing with their dominant hand and with their non-dominant hand and children. We then provide examples of fluency and accuracy for participants producing the three features of an upper-case letter *R*. We finally provide inferential analysis across all stimulus letters and both adult and child samples to determine differential effects of handwriting skill on the production of curved and straight features.

Fluency distributions

Figure 6 shows frequency distributions for the three groups producing straight and curved features. As we suggested in our introduction, modal number of velocity peaks for adults producing straight lines was one, and for producing a curve was two. For straight line, and for many curves, these represent the minimum possible number of velocity peaks. Adults writing with their dominant hand tended, as might be expected, to be maximally fluent. Interestingly, even though the distribution had a longer tail when adults wrote with their non dominant hands, modal number of velocity peaks remained similar in number to those for writing with their dominant hand, and substantially fewer than for our child sample. Given that handwriting with a non-dominant hand is not something that our adult sample will have practiced, this finding is consistent with the assumption that the motor plans underlying competent handwriting are effector-independent (Wing, 2000).

An example: upper-case R

Table 2 gives some summary statistics for adults and children producing the three features of the letter *R*. The adult sample produced all three of these features

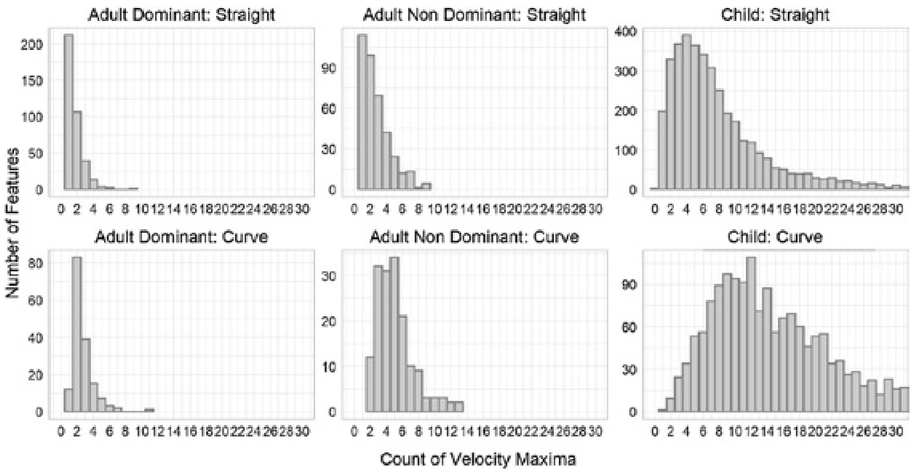

Fig. 6 Distribution of count of velocity maxima (velocity peaks remaining after 10 Hz low-pass filtering) for adults and children producing straight and curved features

Table 2 Descriptive statistics for three features for the letter *R*

	Feature R1 	Feature R2 	Feature R3 
Number inaccurate (%)			
Adult dominant	0 (.0)	0 (.0)	0 (.0)
Adult non-dominant	0 (.0)	0 (.0)	0 (.0)
Child	5 (2.9)	9 (5.2)	15 (8.6)
Number fluent[a] *(%)*			
Adult dominant	20 (74.1)	20 (74.1)	9 (33.3)
Adult non-dominant	9 (33.3)	5 (18.5)	6 (22.2)
Child	6 (3.4)	5 (2.9)	3 (1.7)
Mean velocity peak count (SD)			
Adult dominant	1.26 (.45)	2.30 (1.03)	1.81 (.74)
Adult non-dominant	2.30 (1.32)	4.78 (2.28)	2.41 (1.58)
Child	9.00 (6.28)	11.77 (11.30)	8.64 (7.90)

[a]Fluent here refers to production of the feature with a velocity peak count that corresponds to the mode for the adult sample (1 for straight features, ≤ 2 for curves, see Fig. 8)

accurately in all cases, and inaccuracy was also rare in children. This resulted partly from how the task was set. Both adults and children had the shape of the letter that they were to produce visible in front of them as they wrote. It is also a feature of the coding scheme: The parameters within which a feature must lie are deliberately quite broad, so as to capture any successful attempt at production. Only a subset of these would also be perceived as having been produced neatly.

Pen movement in adults was very much more fluent than in children, even when adults were writing (accurately) with their non-dominant hand (see also Fig. 9). 74% of adults writing with their dominant hand achieved the minimum-possible number of velocity peaks for both features R1 and R2.[4]

Fluency decreased when adults wrote R with their non-dominant hand but, as we have already noted, only slightly. This effect can be clearly seen in the example in Fig. 7. Non-dominant handwriting was definitely slower than when adults wrote normally, and mid-curve deceleration was more pronounced. However,

[4] R3 does not fit this pattern, however, with only 33% of adults achieving maximum fluency. Inspection of the velocity profiles suggests that this was due to adults tending to add a final short pen movement at an acute angle to the end R3. This may be because adults' motor plans are adapted to writing cursively. It may also be because control of diagonal left-to-right finger movement is relatively complex in right-handed writers. Whatever their cause, our segmentation scheme, which was developed for use with children but then applied to adults, allowed for the inclusion of these final short movements. These little flicks were not big enough to break the rules of how features may deviate from prototype features. Bigger flicks would have been classified as inaccurate production of the feature. This highlights the need for carefully developing and testing feature definitions within a specific research context.

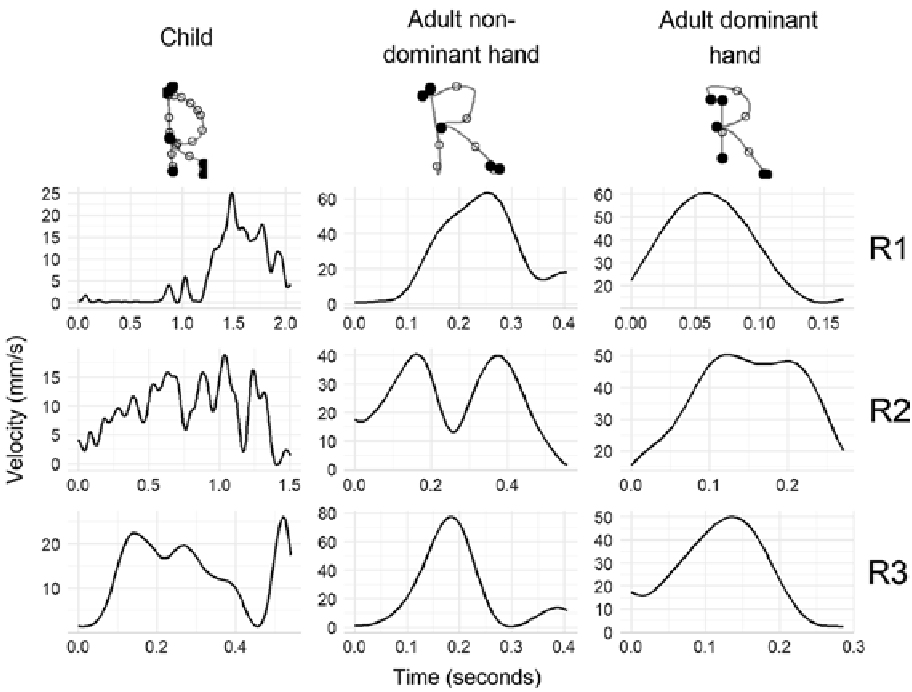

Fig. 7 Examples of velocity profiles for each feature of the letter *R* – R1 (vertical straight), R2_1 (open curve), R3 (diagonal straight) – for a child, and an adult writing with both non-dominant and dominant hand. Open circles in the trace represent locations of velocity peaks. Filled circles represent stops or lifts. Velocity is smoothed with a 10 Hz Butterworth filter

the velocity profile maintained a similar shape to normal production and did not come close to the level of disfluency seen in our child sample.

One question worth asking concerns the relationship between accuracy and fluency. Figure 8 gives velocity plots from four different child writers producing feature R2. This demonstrates again, very clearly, the importance of exploring fluency alongside accuracy. On the basis of their pen traces the children in the top two panels would be identified as skilled handwriters, and the children in the bottom two panels might be identified as being in need of remedial intervention. This is despite the fact that the child in the second panel took 8 times as long to produce the same feature as the child in the first panel. The bottom two panels show faster production suggesting an accuracy fluency trade-off: Inaccuracy in older children is often associated with greater rather than less fluency (van Galen et al., 1993). Analysis of just the child data from the present sample – children at an earlier stage of learning to handwrite than those sampled by van Galen, reported in Fitjar et al., (2021) – did not find this effect, however. We found, instead, that inaccurate features were produced with, on average, 3 more velocity peaks than accurately produced features.

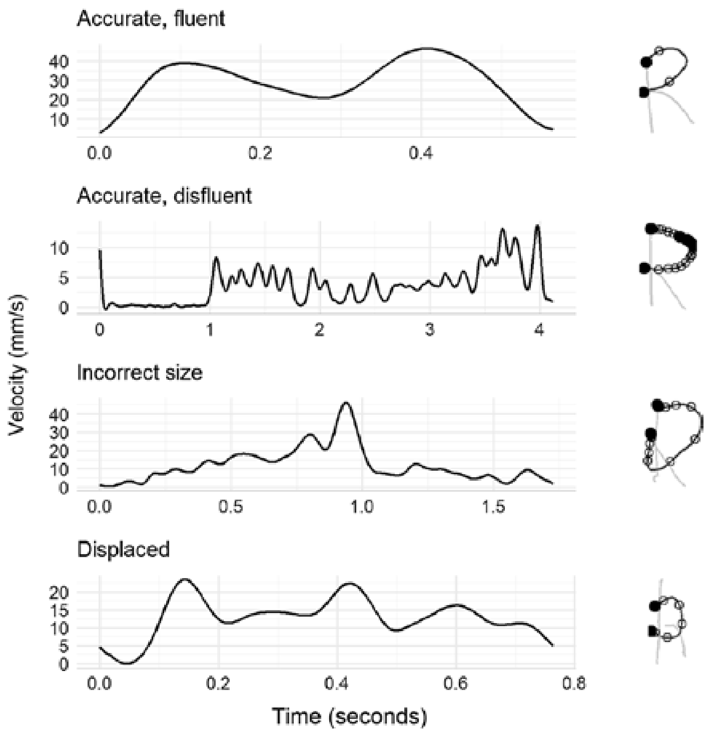

Fig. 8 Pen velocity (smoothed with 10 Hz Butterworth filter) for examples of children producing Feature R2 either correctly or incorrectly, and the resulting trace. Filled circles represent pen lifts or stops. Unfilled circles represent velocity maxima

Effects of feature shape on child and adult fluency

The descriptive statistics and illustrations that we have reported so far suggest that, as might be expected, curved features present a greater graphomotor challenge than straight features, particularly in the early stages of learning to handwrite. In this section we test that hypothesis with data from both adult and child samples. To this end we compared nested linear mixed effects models (e.g., Baayen et al., 2008) predicting velocity peak count and implemented in the lme4 R package (Bates et al., 2015). Model comparison was by likelihood ratio χ^2 test. Statistical significance for parameter estimates for models was established by evaluating against a t distribution with Satterthwaite approximation for denominator degrees of freedom (implemented in lmerTest; Kuznetsova et al., 2017). We started with an intercept-only model, and then added main effects for condition (child, adult dominant-hand, adult non-dominant hand) and whether the feature was straight or curved as fixed effects. This model gave significantly better fit ($\chi^2(1)=70.4$, $p<0.001$). We then added the interaction between these factors (Model 2 vs. M1, $\chi^2(1)=49.3$, $p<0.001$). This final model gave an estimated marginal R^2 of 0.17 (Nakagawa & Schielzeth, 2013),

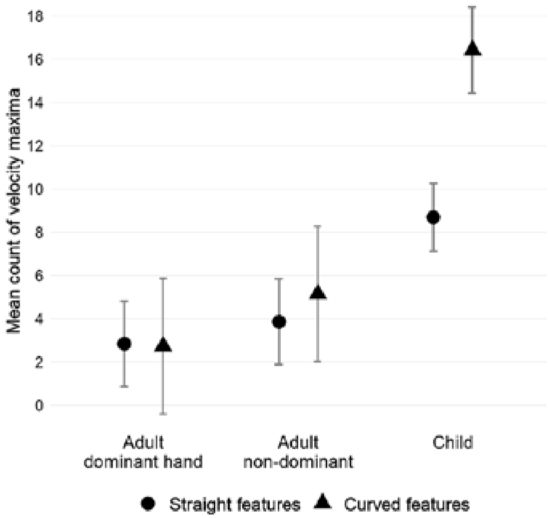

Fig. 9 Observed velocity peak count, after 10 Hz Butterworth smoothing. Error bars represent one standard deviation

and intra-class correlations of 0.26 for random effects of child and 0.16 for random effects of item.

The effects found by the best-fit model can be clearly seen in Fig. 9. Relative to adult writers writing with their dominant hand there was some evidence of a reduction in fluency when adults write with their non-dominant hand (estimated velocity peak increase = 1.0, 95% CI [0.01,2.0], $p = 0.047$) but with no significant additional effect of the feature being curved. Children were substantially less fluent for straight features (5.8 [4.5, 7.2], $p < 0.001$) with a substantial additional effect of 7.9 velocity peaks (95% CI [5.7, 9.9], $p < 0.001$) for children producing curved features.

Conclusion

The aim of this paper was to describe and illustrate a method for segmenting handwritten letter pen-traces into sub-letter features that can then form the basis for an analysis of handwriting fluency. The scheme that we have described also necessarily identifies whether or not a feature has been produced with an acceptable degree of accuracy.

The details of our specific implementation of the approach – our 1/6 tolerance principle and, particularly, our set of acceptable allographs – can and should be varied by users to fit specific research questions, populations, and educational contexts. Our contribution boils down to two observations. First, that if researchers want to make comparisons across writers in handwriting kinesthetics then this must be across features that are, to some meaningful extent, spatially equivalent and that are identified independently of how they are produced. Second, that it is possible to develop a rigorous approach to identifying these features that allows both for variation in absolute size of letter that writers may represent letters using different allographs.

Combined with analysis of movement fluency based on counts of velocity peaks our approach to segmentation and coding scheme therefore allows direct measurement of graphomotor performance. This will be of use to researchers who are directly interested in motor control, providing a more systematic and rigorous approach to pen-trace coding than we were able to find in the existing literature. It will also be of use to researchers who have a broader interest in the cognitive processes that underlie written production, and also in developing strategies for supporting children learning to write. Our approach contrasts, for example, with measures that count the number of characters that are produced in a fixed period of time. These necessarily confound handwriting fluency with time spend in other writing-related processing that occurs when the pen is stationary. Application of this method to real time data from, for example, sentence-copying or written alphabet recall, would allow disambiguation of the contribution of handwriting fluency, per se, to a writer's overall fluency, and the contribution of processes – reading, message processing / stimulus recall, syntactic and orthographic retrieval – that are more likely to occur when the pen is lifted.

Appendix

The table below gives letter segmentation and coding scheme for upper and lowercase letters in the English alphabet. Unless specified, the tolerance for size difference 1/6 of the size of the preceding feature, and the tolerance for gaps/overlaps are 1/6 of letter height.

Letter	Feature code	Shape and orientation	Size	Position
A	A1_1	Straight Diagonal	Similar length to A2	Slant top to right Meet with A2 at top to create an acute angle
	A1_2	Curve, Open	Arms must be similar length	Open end downwards
	A2	Straight Diagonal	Similar length to A1_1	Slant top to left Meets with A1_1 at top to create an acute angle
	A3	Straight Horizonal	Must be long enough to meet with or slightly overlap with A1_1 and A2 or both arms of A1_2	In the middle of A1 and A2

Letter	Feature code	Shape and orientation	Size	Position
B	B1	Straight Vertical	Must be longer than the length of B2	To the left of B2 and B3 Top meets upper arm of B2_1 Bottom meets lower arm of B3_1
	B2_1	Curve Open	The length of the curve must be half the length of B1 and similar to or shorter than B3 Width of curve should be similar to or narrower than width of B3	Open end towards B1 Above B3 Both arms meet B1 Upper arm meets top of B1
	B2_2	Curve, Closed	The length of the curve must be half the length of B1 and similar to or shorter than B3 Width of curve should be similar to or narrower than width of B3	Above B3 The left side meets B1 in the upper half of B1
	B3_1	Curve Open	The length of the curve must be half the length of B1, and similar to or longer than B2 Width of curve should be similar to or wider than width of B2	Open end towards B1 Below B2 Both arms meet B1 Lower arm meets bottom of B1
	B3_2	Curve, Closed	The length of the curve must be half the length of B1 and similar to or longer than B2 Width of curve should be similar to or wider than width of B2	Below B2 The left side meets B1 in the lower half of B1
C	C1	Curve Open	Similar length and width, but length cannot exceed width	Open end towards the right
D	D1	Straight Vertical	Must be longer than the length of D2 Must be long enough to meet both arms of D2	To the left of D2 Cannot extend top of 2 or descend below D2
	D2	Curve Open	Similar length and width, and length must be similar to or shorter than D1 length	Open end towards D1 Upper arm meets top of D1 Lower arm meets bottom of D1

Letter	Feature code	Shape and orientation	Size	Position
E	E1	Straight Vertical	Must be longer than the lengths of E2, E3 and E4	To the left of E2, E3, and E4 Cannot extend above E2 or descend below E4
	E2	Straight Horizontal	Shorter than E1, similar to E4	To the right of E1 Left end meets with top of E1
	E3	Straight Horizontal	Shorter than 1, similar or shorter than 2 and 4	To the right of E1 Left end meets with the middle of E1
	E4	Straight Horizontal	Shorter than E1, similar to E2	To the right of E1 Left end meets with bottom of E1
F	F1	Straight Vertical	Must be longer than the lengths of F2 and F3	To the left of F2 and F3 Top meets left end of F2
	F2	Straight Horizontal	Shorter than F1, similar or longer than F3	To the right of F1 Left end meets with top of F1
	F3	Straight Horizontal	Shorter than F1 and similar to or shorter than F2	To the right of F1 Left end meets with the middle of F1
G	G1	Curve Open	Width must be wider than G2 Arms must be similar length, or bottom arm may be longer than upper arm Curve length cannot be longer than letter height	Open end towards the right
	G2	Straight Horizontal	At least 1/6 of letter height and no longer than letter height	Right end meets with bottom arm of G1 Left end cannot intersect G1
Optional	G3	Straight Vertical	Length cannot extend above G2 or below G1	Top end meets right end G2 Bottom end meets bottom arm of G1
H	H1	Straight Vertical	Similar length to H2	To the left of H2 and H3 The left end of H3 meets with the middle of H1
	H2	Straight Vertical	Similar length to H1	To the right of H1 and H3 The right end of H3 meets with the middle of H2
	H3	Straight Horizontal	Must be long enough to meet with or slightly overlap with H1 and H2 Cannot be longer than both H1 and H2	Meets with H1 and H2 in the middle of H1 and H2
I	I1	Straight Vertical		

Letter	Feature code	Shape and orientation	Size	Position
J	J1	Curve Open	Uneven lengths, left arm must be no more than half the length of the right arm	Open end upwards Below J2 Top of J1 right arm meets J2 in the middle
	J2	Straight Horizontal	Length must be shorter than letter height	Above J1 Middle meets the top of J1 right arm
K	K1	Straight Vertical	Longer than K2 and K3	To the left of K2 and K3
	K2	Straight Diagonal	Shorter than K1 Similar to K3	Slant top to right Bottom meets in the middle of K1
	K3	Straight Diagonal	Shorter than K1 Similar to K2	Slant down to right Top meets in the middle of K1
L	L1	Straight Vertical	Longer than L2	To the left of L2 Bottom meets with left end of L2
	L2	Straight Horizontal	Shorter than L1	To the right of L1 Left end meets with bottom part of L1
M	M1	Straight Vertical	Similar to M4	To the left of M2, M3, and M4 Meet with M2 at top to create an acute angle
	M2_1	Straight Diagonal	Must be at least 1/6 of both 1 and 4 Length similar to length of M3	Slant top to left Top meets with top of 1 to create acute angle Bottom meets with bottom of M3_1, meeting point below the upper 1/6 of letter height
	M2_2	Curve Open	The arms should be similar length, or the right arm may be shorter	Bottom of right arm overlaps with bottom of left arm of M3_2
	M3_1	Straight Diagonal	Must be at least 1/6 of both 1 and 4 Length similar to length of M2	Slant top to right Bottom meets with bottom of M2_1, meeting point below the upper 1/6 of letter height
	M3_2	Curve Open	The arms should be similar length, or the left arm may be shorter	Bottom of left arm overlaps with bottom of right arm of M2_1
	M4	Straight Vertical	Longer than M2_1 and M3_1 Length similar to M1	To the right of M1, M2 and M3 Meet with M3_1 at top to create an acute angle

Letter	Feature code	Shape and orientation	Size	Position
N	N1	Straight Vertical	Length similar to N2 and N3	To the left of N2, and N3 Meets with N2 at top to create an acute angle
	N2	Straight Diagonal	Length similar to N1 and N3	Slant top to left Meets with N1 at top and N3 within lower half to create acute angles
	N3	Straight Vertical	Length similar to 1 and 2	To the right of N1 and N2 Meets with N2 within the lower half to create an acute angle
O	O1	Curve Closed	Similar width and length	
P	P1	Straight Vertical	Length twice the width of the curve in P2	To the left of P2
	P2_1	Curve Open	Width: half the length of P1 Length: shorter or similar to height of P1	To the right of P1 Open end towards P1 Top arm meets with top of P1, and bottom arm meets P1 in the middle
	P2_2	Curve Closed	Width: half the length of P1 Length: shorter or similar to height of P1	To the right of P1 In the upper half of P1
Q	Q1	Curve Closed	Similar width and length	
	Q2	Straight Diagonal	Shorter than the letter height	Slant top to left Meets with or intersects Q1 only once and in the right lower quadrant
R	R1	Straight Vertical	Length twice the width of the curve in R2	To the left of R2 and R3
	R2_1	Curve Open	Width: half the length of R1 Length: shorter or similar to length of R1	To the right of R1 Open end towards R1 Top arm meets with top of R1 Bottom arm meets R1 in the middle
	R2_2	Curve Closed	Width: half the length of R1 Length: shorter or similar to length of R1	To the right of R1 In the upper half of R1
	R3	Straight Diagonal	Shorter than R1	To the right of R1 Slant bottom to right Meets lower arm of R2 and or middle of R1

Letter	Feature code	Shape and orientation	Size	Position
S	S1	Curve Open	Similar to S2 Tolerance: half or double the size of S2	Open end towards right Directly above S2 Lower arm merges into upper arm of S2
	S2	Curve Open	Similar to S1 Tolerance: half or double the size of S1	Open end towards left Directly below S1 Upper arm merges into lower arm of S1
T	1	Straight Vertical	Similar to T2 Tolerance: half or double the size of T2	Below T2 Top meets the middle of T2
	2	Straight Horizontal	Similar to T1 Tolerance: half or double the size of T1	Above T1 Middle meets the top of T1
U	U1	Curve Open	Arms have similar length Length should be longer or similar to width	Open end upwards
V	V1	Straight Diagonal	Similar to V2	Slant top to left Bottom meets with bottom part of V2 to create an acute angle
	V2	Straight Diagonal	Similar to V1	Slant top to right Bottom meets with bottom part of V1 to create an acute angle
W	W1	Straight Diagonal	Longer than or similar to W2 and W3 Similar to W4	Slant top to left Bottom meets with bottom part of W2 to create an acute angle
	W2	Straight Diagonal	Shorter than or similar to W1 and W4 Similar to W3	Slant top to right Bottom meets with bottom part of W1 to create an acute angle Top meets with top of W3 to create an acute angle or intersects upper part of W3
	W3	Straight Diagonal	Shorter than or similar to W1 and W4 Similar to W2	Slant top to left Top meets with top part of W2 to create an acute angle or intersects with upper part of W2 Bottom meets with bottom of W4 to create an acute angle
	W4	Straight Diagonal	Longer than or similar to W2 and W3 Similar to W1	Slant top to right Bottom meets with bottom part of W3 to create an acute angle

Letter	Feature code	Shape and orientation	Size	Position
X	X1	Straight Diagonal	Similar to X2	Slant top to left The middle intersects the middle of X2
	X2	Straight Diagonal	Similar to X1	Slant top to right The middle intersects the middle of X1
Y	Y1	Straight Diagonal	Half the length of Y2	Slant top to left Bottom meets middle of Y2
	Y2	Straight Diagonal	Double the length of Y1	Slant top to right Middle meets end of Y1
Z	Z1	Straight Horizontal	Similar to or shorter than Z2 and similar to or longer than Z3	Above Z2 and Z3 Right end meets top of Z2 to create an acute angle
	Z2	Straight Diagonal	Similar to Z1 and Z3	Between Z1 and Z3 Slant top to right Top meets right end of Z1 to create an acute angle Bottom meets left end of Z3 to create an acute angle
	Z3	Straight Horizontal	Similar to Z1 and Z2	Below Z1 and Z2 Left end meets bottom of Z2 to create an acute angle
a	a1_1	Curve Open	Length similar to a2 length Width similar to length of a2	Open end to the right Aligned with and to the left of a2 Top arm meets top of a2 Bottom arm meets bottom of a2
	a1_2	Curve Closed	Similar length as a2	Top and bottom aligned with a2 top and bottom To the left of a2
	a2_1	Straight Vertical	Similar length as a1	To the right of a1 Overlaps with the right side of a1 OR The top meets end of upper arm of a1_1 and the bottom meets end of lower arm of a1_1
	a2_2	Curve Open	Left arm similar length as a1 Right arm cannot extend the middle of letter height	To the right of a1 Overlaps with the right side of a1 OR The top meets end of upper arm of a1_1, the bottom meets end of lower arm of a1_1

Letter	Feature code	Shape and orientation	Size	Position
b	b1	Vertical	Length twice the width of the curve in b2	To the left of b2 Meets with arms of b2_1 OR the left side of b2
	b2_1	Curve Open	Width: half the length of b1 Length: shorter than length of b1	Open end towards the left To the right of the bottom half of b1
	b2_2	Curve Closed	Width: half the length of b1 Length: shorter than length b1	To the right of the bottom half of b1
c	c1	Curve Open	Similar length and width, but length cannot exceed width	Open end towards the right
d	d1_1	Straight Vertical	Length twice the width of the curve in d2	To the right of d2 and meets d2_1 end of arms OR right side of d2_2
	d1_2	Curve Open	Left arm length twice the width of the curve in d2 Right arm length cannot extend the middle of letter height	To the right of d2 and meets d2_1 end of arms OR right side of d2_2
	d2_1	Curve Open	Length and width: half the length of d1	Open end towards the right Upper arm meets the middle of d1 lower arm meets the bottom of d1
	d2_2	Curve Closed	Length and width: half the length of d1	Meets d1 to the left of the bottom half of d1
e	e1	Straight Horizontal	Length: similar to length of e2 and no more than double the width of e2	Right end meets upper arm of e2 Left arm meets bottom curve of e2
	e2	Curve Open	Length: similar to length of e1 Width: must be at least half of e1 length, but no more than double length of e1 The lower arm must exceed the middle of the upper arm but cannot meet the right end of e1	Open end towards the right The upper arm continues downward to meet the right end of e1

Letter	Feature code	Shape and orientation	Size	Position
f	f1	Curve Open	Arms are uneven length-wise Right arm must be between 1/6 and 1/2 of the length of the left arm Must be longer than f2	Open end downwards Left arm must be in the middle of f2
	f2	Straight Horizontal	Shorter than f1 and longer than 1/3 of f1	Placed cross sectional in the middle of f1, but below endpoint of f1 right arm
g	g1	Curve Open	Arms are uneven length-wise Left arm must be between 1/6 and 1/2 the length of the right arm Must be longer than g2	Open end upwards Must be placed visibly below the bottom curve of g2
	g2_1	Curve Open	Width: half the length of g1 Length: shorter or similar to length of g1	To the left of g1 End of upper arm meets top of g1 Lower arm must be visibly above the bottom of the curve in g1
	g2_2	Curve Closed	Width: half the length of g1 Length: shorter or similar to length of g1	To the left of g1 The right side of the curve meets g1 in the upper half The closed curve must be visibly above the bottom of the curve in g1
h	h1	Straight Vertical	Length: double the length of h2	(Potentially) overlapping with the left arm of h2 Bottom part of h1 should be aligned with end of h2 right arm
	h2	Curve Open	Length: Half the length of h1 Width: shorter or similar to length of h1	Endpoints of h2 arms should be aligned with bottom part of h1 The left arm of h2 may be shorter than the right arm but should be connected to h1
i	i1	Straight Vertical		Ignore tittle
j	j1	Curve Open	Uneven lengths, left arm must be no more than half the length of the right arm	Open end upwards Ignore tittle

Letter	Feature code	Shape and orientation	Size	Position
k	k1	Straight Vertical	Length: longer than k2 and k3	To the left of k2 and k3
	k2	Straight Diagonal	Shorter than k1, Similar to or shorter than k3	Slant top to right Bottom meets in the lower half of k1
	k3	Straight Diagonal	Shorter than k1, similar to or longer than k2	Slant down to right Top meets in the lower half of k1, but not above k2 bottom
l	l1_1	Straight Vertical		
	l1_2	Curve Open	Uneven lengths, right arm must be no more than half the length of the left arm	Open end upwards
m	m1	Straight Vertical	Length: similar to or longer than m2 and m3	(Potentially) overlapping with the left arm of m2 Top should be aligned with top of m2 and m3 curves Bottom part of m1 should be below or aligned with endpoint of m2 right arm and aligned with endpoint of m3 right arm
	m2	Curve Open	Length: similar to or shorter than m1 Left arm length: similar or shorter than m1, similar or longer than m2 right arm Right arm length: similar or shorter than m2 left arm Width: shorter than length, but at least half the length of feature length	Open end downwards Top of curve should be aligned with m3 and top of m1 Left arm should overlap with m1, or start in the upper half of m1 Right arm should overlap with m3 left arm
	m3	Curve Open	Length: similar to or shorter than m1 Left arm: similar or shorter than m3 right arm Right arm: similar or longer than m3 left arm Width: shorter than length, but at least half the length of feature length	Open end downwards Top of curve should be aligned with m3 and top of m1 Left arm should overlap with m2 right arm Right arm endpoint should be below or aligned with endpoint of left arm and aligned with bottom om m1

Letter	Feature code	Shape and orientation	Size	Position
n	n1	Straight Vertical	Length: similar to or longer than length of n2	(Potentially) overlapping with n2 left arm Top should be aligned with top of n2 curve Bottom part of n1 should be below or aligned with endpoint of n2 left arm and aligned with end-point of n2 right arm
	n2	Curve Open	Left arm length: similar to or shorter than n1 and n2 right arm Right arm length: similar to or longer than n2 left arm Width: shorter than length, but at least half the length of feature length	Open end downwards Left arm (potentially) overlapping with n1 Right arm endpoint should be below or aligned with endpoint of left arm and aligned with bottom om n1
o	o1	Curve Closed	Similar width and length	
p	p1	Straight Vertical	Length twice the width of the curve on p2	Meets p2 to the left of p2
	p2_1	Curve Open	Length and width: half the length of p1	To the right of p1 Open end towards p1 Upper arm meets top of p1 Lower arm meets middle of p1
	p2_2	Curve Closed	Length and width: half the length of p1	To the right of p1 Meets in the upper half of p1
q	q1	Straight Vertical	Length twice the width of the curve on q2	Meets q2 to the right of q2
	q2_1	Curve Open	Length and width: half the length of p1	Meets q1 to the left of q1 Open end towards q1 Upper arm meets top of q1 Lower arm meets middle of q1
	q2_2	Curve Closed	Length and width: half the length of p1	To the right of q1 In the upper half of q1
r	r1	Straight Vertical	Length: similar to or longer than length of n2	(Potentially) overlapping with left arm of r2
	r2	Curve Open	Arms are potentially uneven lengthwise, ie left arm may be similar to r1 OR arms are similar in length Right arm must be between 1/6 and 1/2 of the length of the left arm OR r1 length	Open end downwards Left arm overlaps poten-tially with r1, it may be shorter but must be connected to upper half of r1

Letter	Feature code	Shape and orientation	Size	Position
s	s1	Curve Open	Similar to s2 Tolerance: half or double the size of s2	Open end towards right Directly above s2 Lower arm merges into upper arm of s2
	s2	Curve Open	Similar to s1 Tolerance: half or double the size of s1	Open end towards left Directly below s1 Upper arm merges into lower arm of s1
t	t1_1	Straight Vertical	Must be longer than t2	Placed in the middle of t2
	t1_2	Curve Open	Arms are uneven length-wise Right arm must be between 1/6 and 1/2 of the length of the left arm Must be longer than t2	Open end upwards Left arm in the middle of t2
	t2	Straight Horizontal	Shorter than t1 but longer than 1/3 of t1	Placed cross sectional in the middle of t1, but above endpoint of t1_2 right arm
u	u1	Curve Open	Length: longer than width, but no more than double the feature width Width: shorter than length, but at least half the length of feature length	Open end upwards Left arm (potentially) overlapping with u2 Arm endpoints must be aligned
	u2_1	Straight Vertical	Length similar to u1 length	Overlapping with u1 to the right of u1
	u2_2	Curve Open	Left arm similar length as u1 Right arm cannot extend the middle of letter height	To the right of u1 Left arm overlapping with the right arm of u1
v	v1	Straight Diagonal	Similar to v2	Slant top to left Bottom meets with bottom part of v2 to create an acute angle
	v2	Straight Diagonal	Similar to v1	Slant top to right Bottom meets with bottom part of v1 to create an acute angle

Letter	Feature code	Shape and orientation	Size	Position
w	w1	Straight Diagonal	Length shorter than or similar to w1 and w4 Length similar to w3	Slant top to right Bottom meets with bottom part of w1 to create an acute angle Top meets with top of w3 to create an acute angle or intersects upper part of w3
	w2	Straight Diagonal	Length shorter than or similar to w1 and w4 Length similar to w2	Slant top to left Top meets with top part of w2 to create an acute angle or intersects with upper part of w2 Bottom meets with bottom of w4 to create an acute angle
	w3	Straight Diagonal	Longer than or similar to w2 and w3 Similar to w1	Slant top to right Bottom meets with bottom part of w3 to create an acute angle
	w4	Straight Diagonal	Shorter than or similar to w1 and w4 Similar to w3	Slant top to right Bottom meets with bottom part of w1 to create an acute angle Top meets with top of w3 to create an acute angle or intersects upper part of w3
x	×1	Straight Diagonal	Similar to ×2	Slant top to left The middle intersects the middle of ×2
	×2	Straight Diagonal	Similar to ×1	Slant top to right The middle intersects the middle of ×1

Letter	Feature code	Shape and orientation	Size	Position
y	y1_1	Straight Diagonal	Half the length of y2_1	Slant top to left The bottom endpoint meets the middle of y2_1
	y1_2	Curve Open	Length: longer than width, but no more than double the feature width Width: shorter than length, but at least half the length of feature length	Open end upwards Arm endpoints must be aligned Left arm overlaps (potentially) with upper part of y2_2 left arm
	y2_1	Straight Diagonal	Double the length of y1_1	Slant top to right The middle meets the bottom endpoint of y1_1
	y2_2	Curve Open	Arms are uneven lengthwise Left arm must be between 1/6 and 1/2 the length of the right arm Must be longer than y1_2	Open end upwards Left arm overlaps (potentially) with left arm of y1_2 Must be placed visibly below the bottom curve of y1_2
z	z1	Straight Horizonal	Similar to or shorter than z2 Similar to or longer than z3	Above z2 and z3 Right end meets top of z2 to create an acute angle
	z2	Straight Diagonal	Similar to z1 and z3	Between z1 and z3 Slant top to right Top meets right end of z1 to create an acute angle Bottom meets left end of z3 to create an acute angle
	z3	Straight Horizontal	Similar to z1 and z2	Below z1 and z2 Left end meets bottom of z2 to create an acute angle

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Declarations

Ethical approval The study involving human participants was reviewed and approved by Norwegian Centre for Research Data. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

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Paper 2

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Learning Handwriting: Factors Affecting Pen-Movement Fluency in Beginning Writers

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Skilled handwriting of single letters is associated not only with a neat final product but also with fluent pen-movement, characterized by a smooth pen-tip velocity profile. Our study explored fluency when writing single letters in children who were just beginning to learn to handwrite, and the extent to which this was predicted by the children's pen-control ability and by their letter knowledge. 176 Norwegian children formed letters by copying and from dictation (i.e., in response to hearing letter sounds). Performance on these tasks was assessed in terms of the counts of velocity inversions as the children produced sub-letter features that would be produced by competent handwriters as a single, smooth (ballistic) action. We found that there was considerable variation in these measures across writers, even when producing well-formed letters. Children also copied unfamiliar symbols, completed various pen-control tasks (drawing lines, circles, garlands, and figure eights), and tasks that assessed knowledge of letter sounds and shapes. After controlling for pen-control ability, pen-movement fluency was affected by letter knowledge (specifically children's performance on a task that required selecting graphemes on the basis of their sound). This was the case when children retrieved letter forms from dictated letter sounds, but also when directly copying letters and, unexpectedly, when copying unfamiliar symbols. These findings suggest that familiarity with a letter affects movement fluency during letter production but may also point towards a more general ability to process new letter-like symbols in children with good letter knowledge.

Keywords: children, handwriting, fluency, pen-control, letter knowledge

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INTRODUCTION

It is still the case that in nearly all educational contexts children first learn to write by forming letters with pen or pencil on paper. The ability to handwrite is therefore a prerequisite for beginning to write. There is also evidence that, as children write longer texts, ability to retrieve and form letters and words quickly predicts the substantive quality of their written compositions (Feng et al., 2019). Several authors have argued that slow handwritten output not only reduces productivity – important when task duration is limited by time or motivation – but also demands attention that might otherwise be devoted to thinking about higher-level text structures (e.g., Berninger and Winn, 2006; Alves et al., 2016).

Although evidence suggests that handwriting ability is important for successful writing, relatively little is known about the factors that contribute to letter-formation fluency. Studies exploring correlation with text quality, such as those reviewed by Feng et al. (2019) measure handwriting ability using tasks that require reading and copying sentences (Barnett et al., 2009; Olinghouse and Graham, 2009) and/or written alphabet recall (Berninger and Rutberg, 1992; Kent et al., 2014). Successful performance of these tasks requires a broad combination of reading, orthographic, motor, and memory skills. Our present concern is more narrow. We focus specifically on the final, graphomotor components of the cascade of processes that comprise written production. van Galen (1991) describes this as occurring through a combination of allograph selection, size control, and muscle adjustment. These processes take as input an abstract letter representation (a grapheme) and end with the finger and arm movements that give the real-time trajectory of the pen across the page. The aim of the research that we report in this paper was to explore child level factors that predict fluent pen movement when forming letters.

The ability to produce fluent pen movement is, in principle at least, distinct from the neatness or accuracy of the resulting handwritten text. Consider the example in **Figure 1**. In all three cases, the final product is a well-formed (accurate) uppercase A. A classroom teacher looking to correct handwriting inaccuracy would pass over all three without comment. However, time taken to produce the highlighted feature by Writer C was four times longer than for Writer B, and over 10 times longer than for Writer A. The reason for this is clear from the velocity profiles. Whereas Writer A (an adult) produced the feature with a single acceleration and deceleration of the pen-tip, for Writers B and C, both children in early first-grade, pen movement involved multiple velocity inversions (acceleration and deceleration episodes).

There is a developmental trend across primary school years from hesitant pen-movement in early years to smooth, automatic, and ballistic movements in later years (Chartrel and Vinter, 2008; Accardo et al., 2013). The main focus of previous research has been on comparison among children showing neat and untidy handwriting (van Galen et al., 1993; Rosenblum and Werner, 2006; Di Brina et al., 2008; Danna et al., 2013; Asselborn et al., 2018; Gargot et al., 2020). Di Brina et al. (2008) in a sample of second and third grade children examined the similarity in pen-movement trajectory across multiple repetitions of the same letter. Children who were categorised as dysgraphic based on that neatness of their handwriting showed substantially greater variability than students who were classified as good writers, suggesting that differences lie in the extent to which execution is based on stored motor plans. van Galen et al. (1993) used power spectral density analysis – an approach based in signal processing theory – compare children in grades 2–4 identified by their teacher as having poor handwriting to children who wrote neatly. They found that the pen movement of children with poor handwriting showed more power (more movement variation) at frequencies typically associated with movement tremor and less power at frequencies associated with intentional propulsive movement. Rosenblum et al. (2006) compared two groups on several temporal and velocity measures from the production of specific sub-letter features (the two strokes that form the single Hebrew letter ה). Children with teacher-identified dysgraphia were only slightly, and not significantly, slower to form features, but showed substantially more velocity inversions. Danna et al. (2013) compared similar groups on signal-to-noise velocity peaks difference (SNvpd). This is a measure that is conceptually similar to those derived from power spectral density analysis. SNvpd is the difference in counts of velocity peaks, across letters or words, detected after low and after higher waveband filtering. Peaks detected after low waveband filtering are assumed to be peaks that occur as part of fluent, ballistic movement, for example the single peak shown in the upper panel in **Figure 1**. Children with dysgraphia had SNvpd values over twice those of children within normal range handwriting accuracy. Similar measures based in velocity fluctuation discriminate handwriting in children with developmental coordination disorder (Chang and Yu, 2010).

There is, therefore, a relationship between handwriting accuracy (neatness) and the smoothness of the pen-tip speed profile, at least when comparing extreme groups. What is less clear is what underlying abilities predict handwriting ability. Del Giudice et al. (2000) found that accuracy in copying non-letter patterns and figures develops rapidly between the ages of 4 years 6 months and 5 years (20% accuracy to 80% accuracy on a shape copying task) in a sample of children attending kindergarten. There is evidence that shape copying in turn predicts letter copying accuracy in kindergarten (Weil et al., 1994; Marr et al., 2001). Shape copying in kindergarten may (van Hartingsveldt et al., 2015) or may not (Marr and Cermak, 2002) predict letter-writing accuracy in first grade. There is also some evidence that letter knowledge–knowledge of letter shapes and sounds–predicts letter-formation accuracy. Molfese et al. (2011) found that handwriting accuracy in kindergarten correlated with letter and word naming. For 8-10-year-olds, Caravolas et al. (2020) found that spelling ability predicted neatness of letter formation.

Accuracy when forming letters is therefore correlated both with domain-general graphomotor skill and with letter knowledge, as might be expected. Our present purpose is to examine the extent to which these factors affect pen-movement fluency. It would seem very probable that graphomotor skill, based on measures that require pen-control when producing non-letter figures, generalises to the production of letters. The main question addressed in the research that we report in this paper is whether, after control for graphomotor skill, children's general letter knowledge predicts within-letter pen-movement fluency. Specifically we asked whether in situations where children are, for example, copying a letter – i.e., they have a representation of the shape that they aim to produce – general letter-level knowledge, as measured by, for example, the ability to map between phonemes and graphemes, predicts movement fluency. The answer to this question is less straightforward. It may be that retrieval of the letter form – the output from the allograph-selection module in van Galen's architecture for models of handwriting (van Galen, 1991) – is always complete before production of a letter is initiated. If this is the case then we would not expect within-letter pen movement fluency to be affected by letter-knowledge. Alternatively, it may be that, in

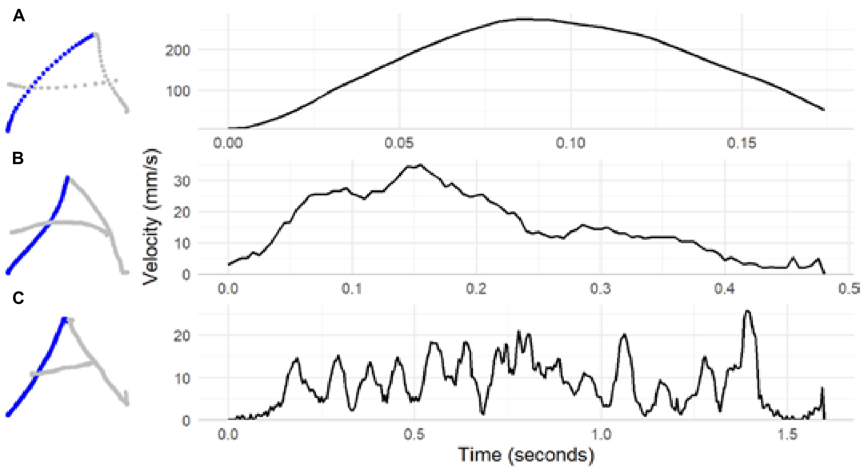

FIGURE 1 | Pen trajectory and velocity profiles for the first feature of the letter A (shown in blue) written by an adult in panel **(A)**, and two first-grade children in panel **(B,C)**.

early writers in particular, letter-knowledge continues to affect movement once pen movement has started, either because they continue to plan the shape that they are forming while the pen in moving, or because allograph knowledge informs the control processes (Meyer et al., 1988; Glover, 2004) that are engaged after movement has been initiated.

Present Study

The study we report in this paper explored predictors of letter-level handwriting fluency in children who were just beginning to learn to handwrite. Our concern was specifically with the final graphomotor components of the cascade of processes that comprise written production. Our focus, therefore, was specifically on a child's ability to move the pen fluently and accurately on the page to create the form of a known letter.

We addressed two questions. In children at the beginning stages of learning to write. . .

(1) To what extent do factors associated with pen-control and with letter knowledge affect pen-tip movement fluency in copied letters and symbols?
(2) After control for letter-copying ability, to what extent do factors associated with letter knowledge affect fluency when forming letters from dictation (i.e., in response to hearing letter sounds)?

We hypothesised, uncontroversially, that handwriting performance would in part depend on pen-control ability (i.e., we hypothesised that ability to fluently reproduce specific pen movements would transfer to the fluent production of letter forms). We also tested the prediction that, after control for graphomotor (pen-control) ability, the extent to which letter features were produced fluently would be dependent on a child's general abstract letter knowledge. This prediction was tested in a character-copying task by the inclusion of unfamiliar symbols as controls. If letter knowledge affects fluency then this effect will be present when children are drawing letters but not when they are producing unfamiliar symbols. Including letter- and symbol-copying performance as covariates in analysis of writing-to-dictation fluency allowed us to isolate effects specifically associated with retrieving letter-form from memory.

MATERIALS AND METHODS

Design and Participants

We report data from 176 first grade children from 10 Norwegian schools who completed various tasks: copying characters, writing letters to dictation, controlling the pen and various letter knowledge measures. Of the 187 children whose parents gave permission, handwriting data from nine children were corrupted and two children were unable to complete any tasks. The children included in the study were on average 74.6 months (6.2 years). There were 90 boys and 86 girls.

Educational Context

In Norway, first grade is the first encounter with formal literacy instruction. Children start first grade in August the year of their sixth birthday. Before they start school, 97.6% of all Norwegian 5-year-olds attend Kindergarten (The Norwegian Directorate for Education and Training, 2020). There is no curriculum with learning goals for the Norwegian kindergarten, but there is a framework that stipulates that children should be encouraged and supported in using language to communicate (The Norwegian Directorate for Education and Training, 2018). Consequently, children enter school in Norway with no formal instruction in either letter knowledge or pen-control.

Equipment and Procedure

Children were tested over 2 days within 4 weeks of school entry. Day 1 was dedicated to testing letter knowledge. Day 2 was dedicated to collecting handwriting and pen-control data. Each child was invited to join the researcher to do the tasks in a quiet room at the school. Each session lasted approximately 20 min. All handwriting and pen-control data were collected with Wacom Intuos XL digitising tablets and HP Elitebook i5 laptops. Pen-tip location was sampled at intervals of around 7.5 ms (133 Hz) and with a spatial resolution of at least 330 lines/cm. An A3 sized paper test-sheet was secured to the tablet and the children wrote with an inking ballpoint stylus. The children were first asked to draw with the pen on the paper and to write their name to familiarise themselves with the equipment. They then completed the pen-control tasks, the copy task, and finally the letter-to-dictation task. Software for pen-movement capture and analysis was provided by the OpenHandWrite suite of programs (Simpson et al., 2021) which provide a digitising tablet interface for PsychoPy (Peirce et al., 2019).

Measures

Copying Task

Children were asked to copy once, in pre-printed boxes of 2.5 × 2.5 cm, each of the following characters: Ø Ω A ‡ M d Ψ h T ɣ e ゐ g R. The researcher showed the child one item at the time, printed on paper (7 cm by 5 cm). The child was then told to write the letter, even if they did not recognise it as we told them there were some "silly" letters as well (these were the non-letter symbols). The child was shown one letter, <Ø>, and one symbol, <Ω>, as practice items. An example pen-trace from this task can be found in **Figure 2**.

After data collection the first and second author manually marked-up the digitised trace of each character produced by children in the copying and dictation tasks. This involved segmenting characters into composite features, identifying temporal and spatial start and end points for each feature. This permitted subsequent analysis of pen-tip velocity profile for the child's production of that feature. Each feature was also coded for accuracy.

FIGURE 2 | Example output from the character copying task, produced by a child with relatively disfluent handwriting. Small circles represent the location in the pen trace of a velocity peak, after 10 Hz filtering.

Feature coding

Segmentation of characters into features was determined by a strict (objective) coding scheme. We identified features as components of characters that competent handwriters would typically produce with a single pen-stroke. Feature definitions were entirely spatial (i.e., defined the shape of the completed feature) and coded independently of information concerning the pen movement with which they were produced. Each character was decomposed into a unique set of curved and / or straight-line features. For example, character <A> was decomposed into three straight-line features, the character <Ø> was decomposed into a straight line and a closed curve, and so forth. We allowed for different allographs. The character <A> could legally also be composed of a single open curve as a replacement for the two diagonal uprights.

Segmented and coded in this way the target characters represented a total of 20 features in letters (14 straight, six curved) and 12 features in non-letter symbols (eight straight, four curved).

Once a feature was identified as present (i.e., could be matched to a feature of the target character), it was coded as either accurate or inaccurate. Our coding scheme was rule based and broadly followed (Reisman, 1993), but defined acceptable feature forms in terms of size, curvature, slope, and curvature relative to other features. A feature was coded as malformed (inaccurate) if it deviated beyond parameters defined as an acceptable representation of an allograph of the target letter. For example the leftmost upright of an uppercase <A>, when formed with two diagonal uprights (the feature identified in **Figure 1**) was coded malformed if it deviated from the following: Meets the second upright at an acute angle of between 20 and 90 degrees not deviate from straight by more than 1/6th of its length, does not deviate in length by more than 1/6th of the length of the second upright, and meets the second upright with separation or overlap of not more than 1/6th of its length. Our coding manual is publicly available (see data availability statement for access).

Feature production fluency

We calculated tangential velocity of the pen-tip at each sample point, and filtered the resulting velocity timecourse with a 10 Hz fourth order low-pass Butterworth filter to remove measurement noise. We then counted remaining velocity maxima for each feature. Features were defined such that competent production could be assumed to be associated with a single velocity maximum (features could be produced with a single pen-stroke). If a child's pen movement when producing the feature was less than fluently, then this would be associated with one or more additional velocity maxima (illustrated in **Figure 1** above). The production of each feature was, therefore, given a disfluency score corresponding to a count of the number of velocity maxima associated with its production.

In pilot data collected using the same measures with adults, currently being prepared for publication, modal number of velocity peaks were one for straight features and two for curves. This provides support for our claim that features in our coding scheme represented letter components that competent handwriters would typically produce in a single ballistic action.

Distribution of this fluency measure, and relationship, at a feature level, with mean velocity, trace length, and duration, are reported in the **Appendix** in **Figures A1**, **A2** respectively.

Dictation Task

In the dictation task the children heard letter-sounds, one at the time, and were asked to write the corresponding letters in pre-printed boxes of 2.5 × 2.5 cm. No instructions were given on how to write the letters (e.g., upper or lower case) and children were told to write the letter as they normally would. The first two sounds were pronounced by the researcher to ensure the child understood the task, then followed nine sounds played by the computer. The first computer-sound was excluded from the analyses as this was more likely to be affected by technical difficulties. The letter-sounds included in the analyses are /l/, /f/, /i/, /b/, /o/, /p/, /u/, /s/, /k/, and /v/. These letters were selected as producing them demands similar motor plans regardless of whether the child chose to write upper or lower-case versions, and therefore the production processes can be compared. That would not be the case for <e> and <E>, which clearly demand different motor plans.

To be identified as an attempt at the target letter in the dictation task, all features associated with the target had to be present, though they could be badly shaped, sized or positioned. Letters identified as successful attempts were then coded for accuracy and fluency measures using the same procedures as for the copying task.

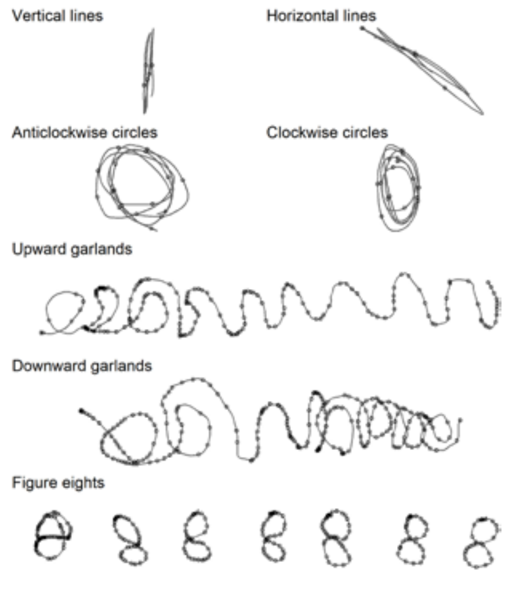

FIGURE 3 | Example output from the various pen-control tasks, produced by the same child as in **Figure 2**. Small circles represent the location in the pen trace of a velocity peak, after 10 Hz filtering.

Pen-Control Tasks

The pen-skill tasks were seven tasks aimed at measuring the child's ability to control the pen. The tasks were adapted from tasks used by Gerth et al. (2016). Example pen traces from these tasks are shown in **Figure 3**.

Straight lines

The tasks were first to draw overlapping horizontal and next overlapping vertical straight lines repeatedly without lifting the pen. The researcher first modelled the pen action, which the child was then asked to reproduce. The children were not stopped until they had produced 10–15 up and down movements or back and forth movements, respectively. The first two lines produced were dropped from analysis. Fluency measures were then taken from the next five consecutive lines made without any pen lifts.

Circles

The tasks were to draw overlapping clockwise and anti-clockwise circles, in each case with a continuous pen movement and with between 10 and 15 repetitions, keeping within a printed box (5 × 7 cm). The researcher first modelled the pen action. The initial two repetitions going in the correct direction were dropped from analysis. Fluency measures were then taken from the next five consecutive circles that were made without any pen lifts. A circle was considered successful if it mainly consisted of one curved line surrounding an open space, with no line crossings before the circle was complete. Round, more egg-shaped, shapes, were accepted.

Garlands

The tasks were to produce first an upward pointing and then a downward pointing garland in a continuous pen movement. The researcher first showed a printed sample of garlands and then modelled the pen action. Each garland was drawn on a pre-printed line (17 cm) with a 4.8 cm gap up to the previous task. The children were encouraged to keep going until they had produced at least ten loops. Fluency measures were extracted across all pen movement during the tasks[1].

Figure eights

The researcher first showed a printed sample of the figure eight and then modelled the pen action required to draw a figure eight as one continuous movement. Children then attempted to reproduce this seven times, drawing each within a separate box (2.5 × 2.5 cm). The fluency measure represents the sum of all the figure eights a child produced.

[1]In some cases children struggled to produce garlands. **Figure 3** gives an example. To establish that there was no accuracy/fluency trade-off, with children achieving greater fluency by failing to correctly form garlands, we scored each sample for accuracy on two dimensions: the extent to which the pen trace formed loops, and loop direction (up or down). A loop is a segment that goes up, back, down, and forward or down, back, up, and forward. Loops were allowed to overlap, but the next loop had to be displaced to the right. Loops could vary in size. Using these criteria we scored each sample for the extent to which the trace was looped: mainly loops (>75%), some loops (25–75%) and almost no loops (<25%). Disfluency (SNvpd) increased from 63.9 in mainly loops group to 72.5 in the some loops group and to 94.6 for the no loops group. i.e., less accurate forms were associated with less fluent production. There was, therefore, no evidence that students traded accuracy for fluency.

The letter features analysed in the copy and dictation tasks have required a small, fixed number of necessary velocity peaks for their production [see, for example, Chartrel and Vinter (2008)]. In the garlands task, however, children varied in how much they produced and in the shape of their output. To control for, this fluency was measured with Signal-to-Noise velocity peaks difference (SNvpd) following the method described by Danna et al. (2013). Following Danna et al., we counted velocity peaks after 5 Hz and after 10 Hz filtering and report the difference. For consistency we also used SNvpd as a measure of fluency on the other three tasks.

Letter Knowledge

Tasks were taken from a battery of tests standardised for use with Norwegian first grade children (Lundetræ et al., 2017; Solheim et al., 2017, 2018).

Phoneme to grapheme encoding

Children heard letter-sounds played on a tablet computer, and then saw four upper-case letters. The children were asked to find and press the letter that corresponded to the sound. Children completed 24 trials, one for each letter of the Norwegian alphabet, excluding *C*, *Q*, *X*, *Y*, and *Z* which are rarely used, with distractor letters chosen randomly. Each trial was scored correct (1) or incorrect (0), and the maximum score was 24.

Grapheme to phoneme decoding

Children saw a lower-case letter on the tablet screen and were asked to speak the letter sound. Children giving letter names were prompted for letter sounds. The target letters were the same as in the previous task. Each trial was scored correct (1) or incorrect (0), and the maximum score was 24.

Phoneme isolation

This was a partial phonological segmentation task in which the children were shown a picture of an object, the researcher named the object, and the child was then asked for the first sound of the name (e.g., "Dette er en bok. Hva er den første lyden i bok?»/"*This is a book. What is the first sound in book?*"). The task terminated after two consecutive failed attempts. Each trial was scored correct (1) or incorrect (0), and the maximum score was 10.

Phoneme blending

The children were shown pictures of four objects or actions and a pre-recorded voice named each word: ri/*ride*, ris/*rice*, ring/*ring*, and rips/*redcurrant* (a high-frequency word for Norwegian children). The pre-recorded voice told the child to press the image corresponding to /r/ /i/ /s/. The children had to blend the sounds to make the word. The task terminated after two consecutive failed attempts. Each trial was scored correct (1) or incorrect (0), and the maximum score was 8.

RESULTS

We evaluated the effects of pen-control and literacy-skill measures on character-writing fluency by comparing a sequence of nested linear mixed effects models (e.g., Baayen et al., 2008), implemented in the lme4 R package (Bates et al., 2015). Our data comprised observations of fluency and accuracy for each character feature drawn by each child. Observations were therefore nested within item (the character) and within child. All models therefore included random by-item and by-child intercepts. Model comparison was by likelihood ratio χ^2 test. Statistical significance for parameter estimates for models with continuous outcomes was established by evaluating against a t distribution with Satterthwaite approximation for denominator degrees of freedom (implemented in lmerTest; Kuznetsova et al., 2017). For generalised linear models, with dichotomous outcomes, we evaluated against a z distribution.

Descriptive statistics for predictor variables (means and bivariate correlations) can be found in **Table 1**. As might be expected, we found strong correlation between our grapheme-to-phoneme decoding and phoneme-to-grapheme encoding ability measures. To avoid issues with collinearity, only the encoding measure was retained on the grounds that this ability is more likely to be causally implicated in grapheme production fluency.

We first give findings from analyses examining factors affecting character copying, and then findings from analyses examining factors affecting writing letters to dictation. In each case our main focus is on factors that affect the extent to which children's pen-tip movement is fluent.

Letter and Symbol Copying

In this section, we explore item-level and child-level factors affecting character copying fluency, measured as the number of velocity peaks in the pen-movement associated with each feature. We started with an intercept-only model, and then added fixed effects incrementally, starting with factors associated with features – Model 1 adds whether or not the feature was correctly formed, and Model 2 adds whether it was a curve. Model 3 adds a fixed effect for whether the character being produced was a letter or symbol. Model 3a adds child age, and Model 4 adds the four pen-control measures. We then explored whether the effects of pen-control measures were moderated by whether the feature being produced was a curve or straight line (Model 5) and whether or not the character was a letter (Model 6). Finally, we added fixed effects for the three letter knowledge measures (phoneme to grapheme encoding, phoneme isolation, and phoneme blending (Model 7) and explored whether these effects were moderated by whether the target being produced was a letter or a symbol (Model 8).

Table 2 details models and model-comparison statistics. Each subsequent model provided better fit, with three exceptions: We found no effect of whether the target was a letter, although this factor was included in subsequent models to permit accurate interpretation of subsequent interaction effects. We also found no effect of child age, or of interaction between letter knowledge measures and whether or not the character was a letter. These factors were omitted from the final model. The best-fit model was, therefore, Model 7. This gave an estimated marginal R^2 of 0.18 (Nakagawa and Schielzeth, 2013), and intra-class correlations of 0.23 for random effects of child and 0.15 for random effects of item.

Parameter estimates from the best-fit model are given in **Table 3**. These indicate the following: (a) when a child produced

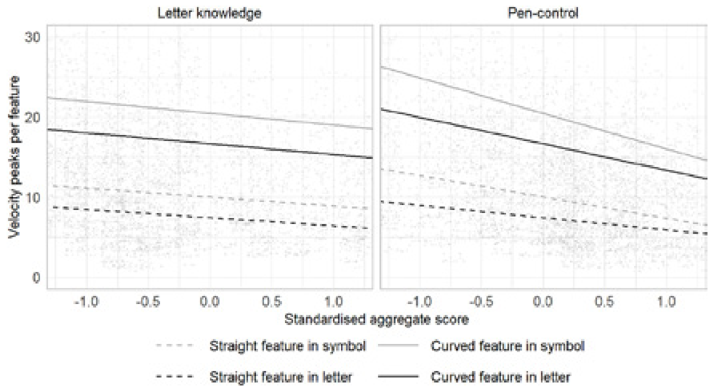

FIGURE 4 | Letter knowledge and pen-control measures as predictors of letters and symbols copying fluency (velocity peaks). Parameter estimates from best-fit model. X-axis values are for just those measures showing statistically significant effect: Letter knowledge is standardised phoneme-to-grapheme encoding score. Pen-control is the reversed mean of standardised fluency measures for garlands and figure-eights. Points represent raw observations.

a badly formed feature, this tended to also be associated with low fluency, (b) curved features were produced less fluently than features comprising straight lines, (c) children's fluency when producing continuous garlands, and particularly figure-eights, predicted character copying fluency, (d) the effect of figure-eight performance on copying fluency was particularly strong when the feature being produced was a curve, (e) effects of pen-control measured by the garlands and figure-eight tasks was slightly greater when copying symbols than when copying letters, and (f) children who performed well on the phoneme to grapheme encoding task showed greater letter and symbol-copying fluency. These findings are illustrated in **Figure 4**.

Interpreting findings related to the fluency of features that were produced accurately compared to those that were malformed requires understanding of how this relates to the shape of the feature and to whether the figure being produced was a letter or a non-letter symbol. Observed proportion of features malformed were as follows: Letters: straight features, *M* = 0.04, *Mdn* = 0.00, IQR [0.00, 0.07]; curved features, *M* = 0.13, *Mdn* = 0.14, IQR [0.00, 0.17]. Symbols: straight features, *M* = 0.09, *Mdn* = 0.00, IQR [0.00, 0.12]; curved features, *M* = 0.32, *Mdn* = 0.25, IQR [0.00, 0.50]. To explore the relationship among these factors we evaluated logistic generalised linear mixed effects models predicting whether or not a feature was formed correctly, starting with an intercept-only model (Model 0), and then adding dummy variables representing whether the feature was straight or curved (Model 1), whether the feature was part of a letter or a symbol (Model 2), and then their interaction (Model 3). We found evidence for an effect of feature shape, with curves produced less accurately [Model 1 vs. Model 0, $\chi^2(1) > 100$, $p < 0.001$], and some evidence that symbols were produced less accurately than letters [Model 2 vs. Model 1, $\chi^2(1) = 4.46$, $p = 0.035$]. There was no evidence of an interaction between these factors.

TABLE 1 | Mean scores and bivariate correlations among letter-knowledge, pen-control, and copying letters and symbols fluency measures.

	Mean (SD)	Isolation	Blending	Encoding	Decoding	Lines	Circles	Garlands	Eights	Copy letters
Phoneme isolation	6.2 (3.6)									
Phoneme blending	3.5 (2.5)	0.56								
Phoneme to grapheme encoding	18 (5.6)	0.59	0.51							
Grapheme to phoneme decoding	11 (6.8)	0.69	0.60	0.72						
Pen-control: Lines	0.46 (1.4)	−0.07	−0.08	0.01	−0.04					
Pen-control: Circles	6.7 (5.8)	−0.11	−0.26	−0.11	−0.09	0.40				
Pen-control: Garlands	61 (41)	0.09	0.02	0.04	−0.00	0.18	0.24			
Pen-control: Eights	98 (52)	0.00	−0.00	−0.12	−0.16	0.04	0.04	0.30		
Copy-fluency: Letters	10 (4.3)	−0.16	−0.13	−0.32	−0.30	0.09	0.20	0.19	0.41	
Copy-fluency: Symbols	13 (5.8)	−0.03	−0.02	−0.16	−0.19	0.05	0.16	0.26	0.45	0.70

$p < 0.001$ for $|r| > 0.25$. For pen-control, measures are SNvpd values across the entire task. For copy fluency, values are for mean number of velocity peaks (10 Hz filtering) per feature, averaged within and then across participants.

TABLE 2 | Model comparison for models predicting pen-movement disfluency (velocity peak count) in the character copying task.

	Fixed factor(s) added	X^2, df, *p*
Model 1	Feature malformed (vs. correct)	100, 1, <0.001
Model 2	Target feature is a curve (vs. straight line)	420, 1, <0.001
Model 3	Character is a letter (vs. symbol)	2.2, 1, 0.136
Model 3a	(Child age)	0.09, 1, 0.77
Model 4	Pen-control measures	52, 4, <0.001
Model 5	Interactions between pen-control measures and whether the target feature is a curve	35, 4, <0.001
Model 6	Interactions between pen-control measures and whether the character is a letter	13, 4, 0.013
Model 7	Letter-knowledge measures	10, 3, 0.017
Model 8	Interactions between literacy-ability measures and whether the character is a letter	4.2, 4, 0.24

Models were nested, with all fixed factors added at a particular stage carried forward to subsequent model, with the exception of age (Model 3a). Model 1 was compared with an intercept-only model. Model 7 is the best fit model.

TABLE 3 | Pen-movement disfluency (velocity peak count) when copying characters.

	Main effects	Interaction with Feature-is-curve	Interaction with Character-is-letter
Intercept	10 [8.0, 12]		
Feature is malformed (vs. correct)	3.0 [2.1, 3.9]***		
Feature is a curve (vs. straight line)	7.3 [6.7, 8.0]***		
Character is a letter (vs. symbol)	−2.1 [−4.8, 0.52]		
Pen−control fluency			
Lines	−0.31 [−1.0, 0.42]	0.12 [−0.46, 0.70]	0.32 [−0.24, 0.87]
Circles	0.55 [−0.20, 1.3]	0.53 [−0.06, 1.1]	−0.06 [−0.63, 0.50]
Garlands	0.73 [0.01, 1.5]*	0.37 [−0.21, 0.94]	−0.56 [−1.1, −0.00]*
Figure eights	1.8 [1.1, 2.5]***	1.3 [0.70, 1.8]***	−0.58 [−1.1, −0.05]*
Letter knowledge			
Phoneme to Grapheme encoding	−1.1 [−1.8, −0.34]**		
Phoneme isolation	0.01 [−0.74, 0.75]		
Phoneme blending	0.36 [−0.35, 1.1]		

*Estimated effects with 95% CI. Parameter estimates from a linear mixed-effects model with random by-item and by-subject intercepts. Blank cells indicate that effect was absent in the best-fit model. *p < 0.05; **p < 0.01; ***p < 0.001.*

Writing Letters to Dictation

Two children failed to retrieve any letters in the letter-writing to dictation task. These children are therefore omitted from this analysis. For the remainder of children, the median number of correct responses (responses that were identifiable as the target letter but may have included one or more malformed features) was 5 (IQR [4,8]) out of a maximum of 10. The analyses that follow are just of data from correct responses. In the resulting sample, the mean number of straight features included for each child was 7.82 (*SD* = 3.15) and curved features, *M* = 5.38, *SD* = 1.58.

We explored whether children's letter knowledge predicts production fluency, over and above variance explained by children's performance on the letter-copying task as follows: We started with an intercept-only model, and then added a dummy variable to control for whether or not the feature was malformed (Model 1). We then added measures of letter-copy and symbol-copy fluency, taken from the letter-copying task and aggregated within child (Model 2). Finally, we added the three letter knowledge measures (Model 3). We performed this analysis separately for straight and curved features. For straight features, each subsequent model provided better fit [$\chi^2(1) = 10$, $p = 0.001$; $\chi^2(2) = 26$, $p < 0.001$; $\chi^2(3) = 10$, $p = 0.017$, respectively]. Model 3, the best fit model, gave an estimated marginal R^2 of 0.10, and intra-class correlations of 0.38 for random effects of child and 0.06 for random effects of item. For curved features, Models 1 and 2 both improved fit [$\chi^2(1) = 4.5$, $p = 0.034$ and $\chi^2(2) = 80$, $p < 0.001$] but we found no evidence of an effect of letter knowledge [Model 3, $\chi^2(3) < 1$]. Estimated marginal R^2 was 0.13 for Model 2, the best fit model, with intra-class correlations of 0.13 for random effects of child and 0.21 for random effects of item.

Parameter estimates from the best-fit models are given in **Table 4**. Effects of letter and symbol-copying ability were similar for both straight and curved features. As might be expected, lack of fluency in copying was associated with lack of fluency when producing letters that were retrieved in response to their sounds, although this effect failed to reach significance for symbol copying as a predictor of straight feature production. The production of curved features was generally less fluent, as was the case for the letter and symbol-copying tasks but we found no evidence for effects of children's letter knowledge. There was some evidence of effects of letter knowledge for straight features over and above variance explained by children's

TABLE 4 | Parameter estimates from models predicting disfluency (velocity peak count) when children wrote letters to dictation.

	Straight features	Curved features
Intercept	6.6 [5.4, 7.7]	10 [7.9, 12]
Feature is malformed (vs. correct)	5.2 [1.8, 8.7]**	2.0 [0.12, 3.8]*
Symbol copying fluency	0.97 [−0.24, 2.2]	1.0 [0.37, 1.7]**
Letter copying fluency	1.5 [0.23, 2.7]*	1.8 [1.1, 2.5]***
Phoneme to Grapheme encoding	−1.2 [−2.3, −0.02]*	
Phoneme isolation	−0.95 [−2.1, 0.22]	
Phoneme blending	1.2 [0.06, 2.3] *	

*Parameter estimates from a linear mixed-effects model with random by-item and by-subject intercepts. Blank cells indicate that effect was absent in the best-fit model. *p < 0.05; **p < 0.01; ***p < 0.001. All predictor variables were standardised, with the exception of the dummy variable representing malformed features.*

performance on the letter-copying task. As was the case with copying, good performance on the phoneme to grapheme encoding task was associated with more fluent production. However, phoneme blending showed the reverse effect. We suspect that this is a statistical artefact resulting from relatively strong correlations among our letter knowledge measures, rather than representing a true effect.

When writing letters to dictation, the children who managed to reproduce the target letter tended to include all features in the correct shape, position and size, with 157 children (90%) making no errors on straight features, and 137 (79%) making no errors on curves.

DISCUSSION

Our analysis focussed on fluency of production of letter features, in beginning writers, that skilled adult handwriters would typically produce in one smooth, ballistic movement. We found that children in our sample typically produced these features disfluently, with multiple velocity inversions where skilled performance would result in only one or two. This is as might be expected given the lack of pre-school training in handwriting in the Norwegian educational system. Chartrel and Vinter (2008), using a velocity peak measure very similar to the one used in this study, found rather greater letter-copying fluency in children in the last year of French kindergarten. Curved features were produced less fluently than straight features, in both the copying and dictation tasks. In the relatively rare cases where a feature was malformed, these tended to also be produced with less fluency, again in both tasks.

We found, again as might be expected, that pen-control ability, measured by fluency when producing garlands and figure-eights, predicted fluency when copying characters. This effect was somewhat greater for curved features, and when copying non-letter symbols. Children with good letter knowledge, and specifically phoneme-to-grapheme encoding ability, copied both letters and symbols with greater fluency. When writing-to-dictation, with statistical control of letter-copying fluency, phoneme-to-grapheme encoding predicted fluency for straight features but not for curved features.

We first discuss effects of pen control and then effects of letter-knowledge. Fluency in the garlands and figure-eights tasks independently predicted character copying fluency, but fluency in the straight line and circles pen-control tasks did not. This was, we believe, for one or both of two reasons. First, these tasks did not discriminate between children in our sample. Mean number of super-numerous velocity peaks–velocity inversions that would not be expected in a handwriting–was roughly one per circle, when children drew circles, and were largely absent when children drew straight lines. This probably simply reflected the developmental stage of our sample. Although they had had little or no formal training in handwriting prior to data collection, at a mean age of 6.2 years their motor development and hand-eye coordination is likely to have been relatively advanced. Garlands and figure eights were substantially more challenging tasks for reasons including the fact that both figures include inflection points at which the direction of curvature changed. Second, drawing garlands and, particularly, isolated figure eights is not only a more complex skill but one that is closer to the specific abilities required to project letters and letter-like symbols. In both cases the pen movement was first presented to the child. However, we suspect that, unlike the repeated movement required for the lines and circles tasks, both of these tasks made direct demands on graphomotor skills (the ability to take a mental representation of a figure and reproduce it on the page).

Letter-knowledge, specifically performance on a phoneme-grapheme encoding task, also predicted pen-movement fluency. This is, perhaps, a more surprising finding. Existing models of handwriting production assume that grapheme and, in fact, allograph selection is complete before the movement to form a letter starts, even in early writers (van Galen, 1991; Pagliarini et al., 2017). Letter knowledge might, therefore, affect latency prior to starting a letter, but not movement fluency while the letter features are being drawn. There is, however, evidence that for children with a specific cognitive literacy deficit (dyslexia but not dysgraphia) the rhythmic nature of handwritten word production, that is present in even young children, breaks down (Pagliarini et al., 2015). This could be interpreted as suggesting that, at least in extreme cases, difficulty with mapping between graphemes and phonemes can result in pen-movement disfluency within letters rather than hesitation between letters or words.

Therefore one possible explanation of the association between letter-knowledge and within-feature fluency was that lack of knowledge directly interferes with production, either because motor planning is not complete at start-of-movement or because uncertainty activates control processes that then modify the planned action (Glover, 2004). This account does not, however, explain the fact that effects were present not only when participants were forming letters, but also when copying non-letter symbols. We suggest two further explanations. It may be that a precursor to developing good knowledge of phoneme-grapheme correspondence is the visuo-spatial ability to process novel letter-like shapes. This ability, in turn, is likely to increase fluency when copying unfamiliar symbols. This will particularly have been a factor if some children interpreted the copying task as requiring exact reproduction of the allograph with which they were presented, which will have necessarily been the case for characters that they did not recognise. A third possibility is that the direction of causality is reversed. Students who are able to handwrite fluently will be more productive. Practicing forming letter by hand may result in improved abstract letter knowledge (Longcamp et al., 2008; Bara and Bonneton-Botté, 2018; but see Bara et al., 2016), although this is more likely to occur when children have been exposed to formal, classroom writing instruction, which was not the case for our sample. The three explanations that we have offered are not mutually exclusive, and all three mechanisms may have been at play in our study. Future research could usefully aim at isolating these different effects.

Effects on fluency when forming letters in response to dictation were dependent on whether or not the letter feature was curved. For curved features fluency was predicted just by fluency on the letter copying task, with effects both for symbol copying and for letter copying. This suggests that, for curves–which were generally less fluently produced and therefore more graphomotorically demanding, performance was overdetermined by pen control ability. For straight lines residual variance was explained in part by letter-knowledge. As for the copy task we found that fluency was greater for children with better phoneme-to-grapheme encoding ability. However, we found that children who performed well on the blending task–an ability that requires phonological skill but not grapheme recognition–were less fluent, after control for the other two letter-knowledge variables. We do not have a straightforward explanation for this effect.

Finally, it is worth noting that, unlike studies with older children (e.g., van Galen et al., 1993) we did not find evidence of a trade-off between fluency and accuracy. In the relatively rare cases where the children in out sample produced letter features that were badly formed these tended to also be produced less fluently. Once some level of automaticity has been achieved then children have the flexibility to jettison some of control in the interests of writing with greater fluency, and therefore greater speed. However, our data suggests that the majority of children in our sample were not at a stage where they had the option to produce letter features with these less controlled, ballistic actions.

In summary, therefore, our paper presents a first attempt at unpacking factors that predict within-letter pen-movement fluency in beginning writers. As such, we have started to explore one of a number of components that contribute to transcription fluency as measured, for example, by speed of sentence copying (e.g., Barnett et al., 2009). A number of previous studies have demonstrated that children with untidy handwriting produce pen strokes with multiple velocity inversions, indicating a lack of automaticity and the need for ongoing motor-planning and correction after movement has been initiated. Our study started from the observation across children who correctly and neatly form letters–children who would not be identified by teachers as having difficulty with handwriting–there is considerable variation in fluency. Neat handwriting may therefore mask disfluency that has knock on effects for productivity and, perhaps, composition quality. Our findings indicate that disfluency is associated not just with weaker graphomotor (pen-control) ability but also with more general abstract letter knowledge. It would be premature to draw implications for instruction based on these findings. However, we recommend that future research gives attention to stroke fluency, alongside more macro-level fluency measures, in seeking to understand how children develop the complex cascade of processes that combine to permit fluent written composition.

DATA AVAILABILITY STATEMENT

Data, scripts for statistical analysis and manual for coding letter features from this study are available at: https://doi.org/10.17605/OSF.IO/P8JBF.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Norwegian Centre for Research Data. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

AUTHOR CONTRIBUTIONS

All authors contributed to the development and design of the study. CF and VR performed testing and data collection. CF, VR, and MT analysed the data and drafted the manuscript.

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

APPENDIX: SUPPLEMENTARY ANALYSES

Distribution of Velocity Peaks Measure

Figure A1 gives the distribution of our fluency measure, broken down by feature type (straight, curved) and condition (letters and symbols produced in the copy task and letter produced in response to dictation).

Correlations Among Fluency, Speed, Trace Length, and Duration

The following plot in **Figure A2** shows the relationships among these different kinematic measures. Each point on the plot represents that production of one feature by one child, combining data from the copy task (both letters and symbols) and the dictation task. Trace length refers to the total length of the line created as the child produced the feature. Speed is mean speed across production of the feature (trace-length divided by duration). Points are jittered slightly for clarity.

We estimated bivariate correlations among these variables by means of linear mixed effects models with random by-feature and by-child slopes and intercepts. For each pair of measures a model including the predictor variable provided significantly and substantially better fit than model with just random effects [$\chi^2(1) > 100$, $p < 0.001$ for all four models]. Correlation (standardised univariate regression) estimates were as follows: Velocity peak count (disfluency) and speed, -0.63, 95% CI [-0.70, -0.55]; length and duration, 0.49 [0.44, 0.54]; velocity peak count and duration, 0.99 [0.96, 1.0]; velocity peak count and length,.37 [0.32, 0.43].

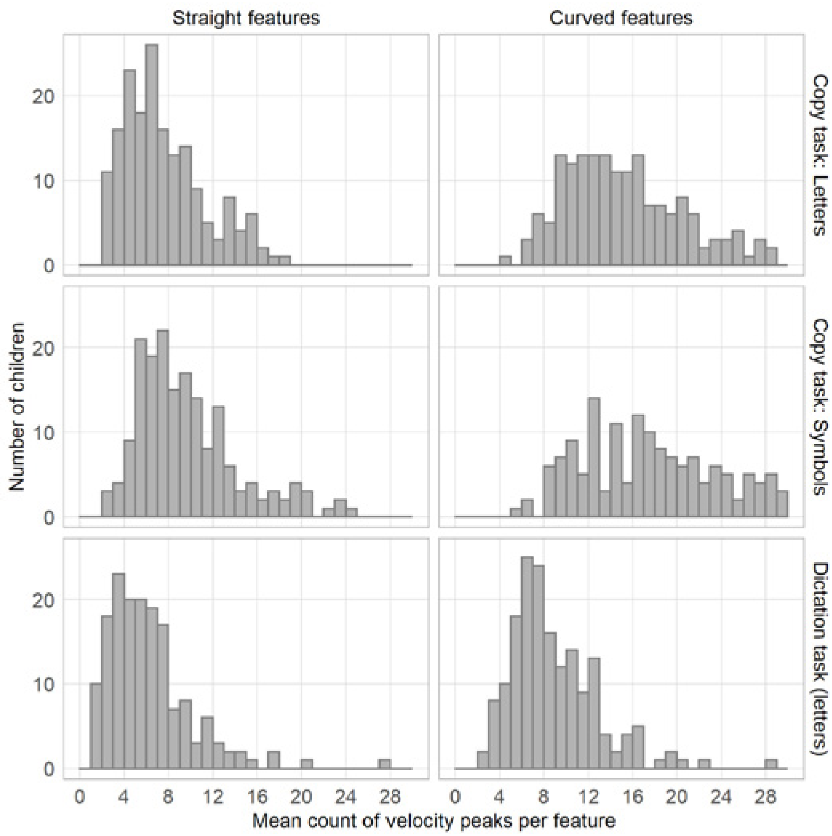


FIGURE A1 | Distribution of velocity peaks.

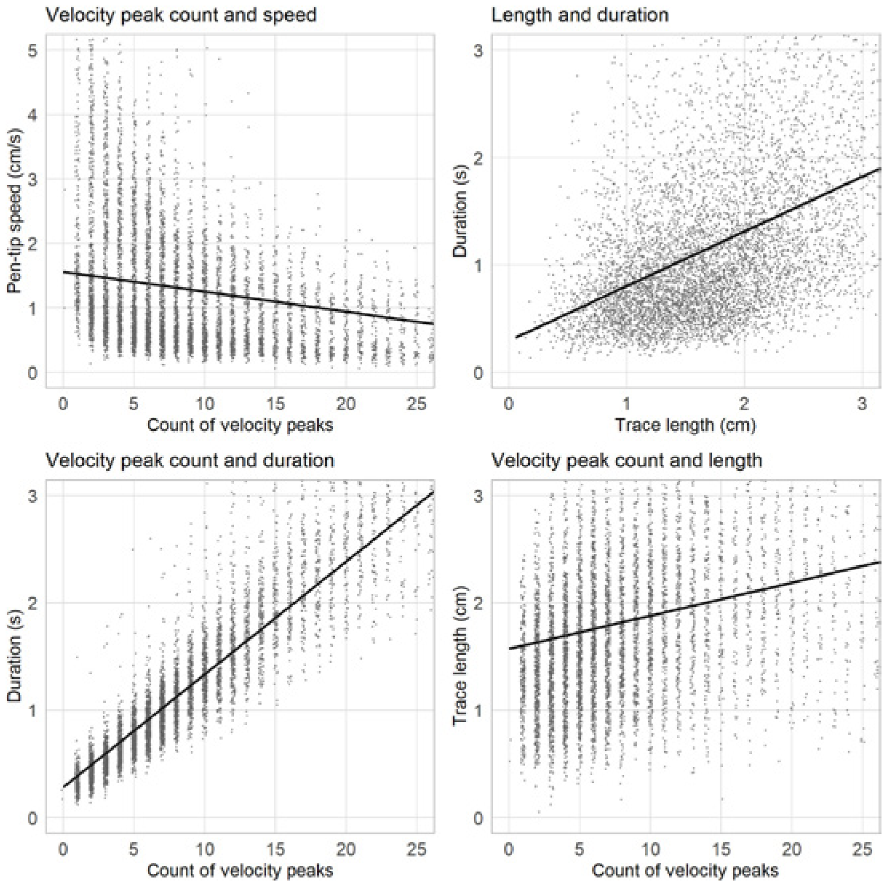


FIGURE A2 | Correlations among fluency, speed, trace length, and duration.

Paper 3

Fitjar, C. L. (prepared for submission). Lexical processing does not affect motor execution within the word initial letter when beginning writers write single words to dictation

Please note: This paper is not included in the repository because it has not yet been published.

Appendices

Appendix 1 – Letter of consent

Invitasjon til deltaking i forskingsprosjektet DIGIHAND

Bakgrunn og føremål

DigiHand er eit forskingsprosjekt som undersøker handskriftsutviklinga til elevar når nettbrett blir nytta i begynnaropplæring i lesing og skriving. Studien tek føre seg klasserom som nyttar handskriftinstruksjon frå første klasse og dei klasseroma som ventar med handskrift til andre klasse. Prosjektet er leia av Høgskulen i Volda i samarbeid med Lesesenteret på Universitetet i Stavanger, og finansiert av Forskingsrådet.

Vilkåra for å delta er skular som nyttar nettbrett frå 1.klasse, som har nynorsk som hovudmål og med ein klassestorleik på minimum 10 elevar. Dykkar skule har sagt ja til å delta i *DigiHand*, så no treng vi samtykke frå føresette for å kunne gjennomføre studien. Prosjektet vil omfatte ei utveljing av klassar som startar i 1. klasse hausten 2018.

Kva vil deltaking i denne studien innebere?

Ved skulestart, i slutten av første og slutten av andre klasse vil vi kartlegge elevane sine lese- og skriveferdigheiter. Denne kartlegginga vil skje individuelt på skulen og vare i omlag 15 minutt. Vi legg vekt på at elevane skal ha ei positiv oppleving av denne prosessen og vil gjennomføre kartlegginga ved bruk av nettbrett. I tillegg vil læraren samle inn nokre elevtekstar kvart halvår som elevane skriv, og desse vil bli brukt til å studere skriveutvikling. Nokre klassar vil bli valde ut til å delta i videofilming av undervisninga. Dette vil skje gjennom tre periodar i løpet av 1. og 2.klasse, der tre undervisningsøkter vil verte filma i kvar periode.

Kva vil skje med informasjonen om ditt barn?

All personleg informasjon vil bli handtert konfidensielt. Berre hovudforskarane vil ha tilgang til denne informasjonen. Alle data vil bli anonymisert. Ei liste med namn og personidentifiserbar opplysningar vil bli halden separat frå andre data, og lagra i eit låsbart skap. Videomateriale som vert samla inn vil verte lagra på forsvarleg måte og vil verte analysert på datamaskiner som ikkje er kopla opp mot internett.

Resultat som vert publisert, vil ikkje innehalde nokon form for personleg informasjon eller noko som kan bli brukt for å identifisere dei som deltek. Det vil ikkje vere mogleg å kjenne att elevar eller lærarar i samband med prosjektet.

Frivillig deltaking – etiske omsyn

Deltaking i studien er heilt frivillig og de kan trekkje barnet frå studien når som helst. All informasjon om barnet som trekkjer seg frå studien vil då bli sletta. Aktivitetane i prosjektet vil også vere læringsfremjande ved at dei engasjerer elevane og liknar dei oppgåvene dei elles gjer. Prosjektet blir avslutta den 31.12.2021, og alle personidentifiserbare opplysningar vil då bli sletta.

Om ein har spørsmål til studien, kan ein kontakte prosjektleiar Wenke Mork Rogne, Høgskulen i Volda tel.: 70075108 eller 48031667, e-mail: wenkemr@hivolda.no eller forskingsleiar Siv Måseidvåg Gamlem, Høgskulen i Volda, tel.nr.: 70075376, e-mail: sivmg@hivolda.no

……………………………………………………………………………………………

Samtykke til deltaking i studien

Eg har tatt imot informasjon om studien *DigiHand*, og ønskjer å la ________________ delta.
(Eleven sitt namn)

(Signert av føresette, dato)

Appendix 2 – NSD approval

Wenke Mork Rogne
Postboks 500
6101 VOLDA

Vår dato: 02.05.2018 Vår ref: 59799 / 3 / LAR Deres dato: Deres ref:

Tilrådning fra NSD Personvernombudet for forskning § 7-27

Personvernombudet for forskning viser til meldeskjema mottatt 13.03.2018 for prosjektet:

59799	*DigiHand*
Behandlingsansvarlig	*Høgskulen i Volda, ved institusjonens øverste leder*
Daglig ansvarlig	*Wenke Mork Rogne*

Vurdering

Etter gjennomgang av opplysningene i meldeskjemaet og øvrig dokumentasjon finner vi at prosjektet er unntatt konsesjonsplikt og at personopplysningene som blir samlet inn i dette prosjektet er regulert av § 7-27 i personopplysningsforskriften. På den neste siden er vår vurdering av prosjektopplegget slik det er meldt til oss. Du kan nå gå i gang med å behandle personopplysninger.

Vilkår for vår anbefaling

Vår anbefaling forutsetter at du gjennomfører prosjektet i tråd med:

- opplysningene gitt i meldeskjemaet og øvrig dokumentasjon
- vår prosjektvurdering, se side 2
- eventuell korrespondanse med oss

Meld fra hvis du gjør vesentlige endringer i prosjektet

Dersom prosjektet endrer seg, kan det være nødvendig å sende inn endringsmelding. På våre nettsider finner du svar på hvilke endringer du må melde, samt endringsskjema.

Opplysninger om prosjektet blir lagt ut på våre nettsider og i Meldingsarkivet

Vi har lagt ut opplysninger om prosjektet på nettsidene våre. Alle våre institusjoner har også tilgang til egne prosjekter i Meldingsarkivet.

Vi tar kontakt om status for behandling av personopplysninger ved prosjektslutt

Ved prosjektslutt 31.12.2021 vil vi ta kontakt for å avklare status for behandlingen av personopplysninger.

Se våre nettsider eller ta kontakt dersom du har spørsmål. Vi ønsker lykke til med prosjektet!

Dokumentet er elektronisk produsert og godkjent ved NSDs rutiner for elektronisk godkjenning.

Vennlig hilsen

Marianne Høgetveit Myhren

Lasse André Raa

Kontaktperson: Lasse André Raa tlf: 55 58 20 59 / Lasse.Raa@nsd.no
Vedlegg: Prosjektvurdering

Personvernombudet for forskning

Prosjektvurdering - Kommentar

Prosjektnr: 59799

FORMÅL
Formålene med studien beskrives som følger:

- Få meir forskingsbasert kunnskap i lærarutdanningane om skrivepraksisen i begynnaropplæringa i norske klasserom
- Kompetansebygging i to lærarutdanningsinstitusjonar når det gjeld tidleg språkutvikling gjennom studiet av handskriftsutvikling i digitale klasserom.
- Kompetansebygging og implementering av forskingsresultat relatert til bruk av nettbrett i lese- og skriveopplæringa

UTVALG
Skoleelever som begynner i første klasse høsten 2018 samt deres foreldre og lærere.

INFORMASJON OG SAMTYKKE
Dere har opplyst i meldeskjema at utvalget vil motta skriftlig og muntlig informasjon om prosjektet, og samtykke skriftlig til å delta. Vår vurdering er at informasjonsskrivet til utvalget er hovedsakelig godt utformet.

Vi legger til grunn at det legges opp til et alternativt opplegg for elever som ikke deltar i forskningsprosjektet, jf. e-brev av 16.04.2018 fra daglig ansvarlig. Dette må også fremgå klart av informasjonen til utvalget, slik at valget om deltakelse fremstår som reelt frivillig.

TREDJEPERSONOPPLYSNINGER
Det bemerkes at dersom en forelder fyller ut spørreskjemaet alene, vil det kunne fremkomme opplysninger om den andre forelderen uten at denne har samtykket til dette. Tema vil være forelderens morsmål og utdanningsnivå, samt hvilket språk forelderen snakker mest med barnet. Opplysningene oppleves som nødvendig for prosjektets formål; de er videre av begrenset omfang, ikke sensitive, og de vil anonymiseres i publikasjonen.

I den grad det er mulig, bør forelderen som fyller ut spørreskjemaet informere den andre forelderen om at vedkommendes personopplysninger registreres. Dersom dette er uforholdsmessig vanskelig, vurderer personvernombudet at det kan unntas fra informasjonsplikten jf. personopplysningsloven § 20 b.

SENSITIVE TREDJEPERSONOPPLYSNINGER
Personvernombudet legger til grunn at det ikke fremkommer sensitive opplysninger om den andre forelderen eller om andre identifiserbare tredjepersoner uten at det innhentes samtykke til dette i forkant fra den det gjelder. Dersom det ikke innhentes samtykke fra tredjeperson, må spørsmål om lese- og skrivevansker i barnets nære familie formuleres på en slik måte at ingen kombinasjoner av svaralternativer kan identifisere

enkeltpersoner, jf. personvernombudets korrespondanse med daglig ansvarlig.

BARN I FORSKNING

Selv om barnets foresatte samtykker til barnets deltakelse i prosjektet, må også barnet gi sin aksept til å delta. Vi anbefaler at barnet mottar tilpasset informasjon om hva deltakelse i prosjektet innebærer. Dere må sørge for at barnet forstår at deltakelse er frivillig, og at det kan trekke seg om det ønsker det.

SENSITIVE OPPLYSNINGER

Det fremgår av meldeskjema at dere vil behandle sensitive opplysninger om helseforhold. Det bør utøves særlig forsiktighet ved behandling av sensitive personopplysninger, både når det gjelder etiske problemstillinger, innhenting av data og informasjonssikkerhet underveis.

DATASIKKERHET

Personvernombudet forutsetter at du/dere behandler alle data i tråd med Høgskulen i Volda sine retningslinjer for datahåndtering og informasjonssikkerhet.

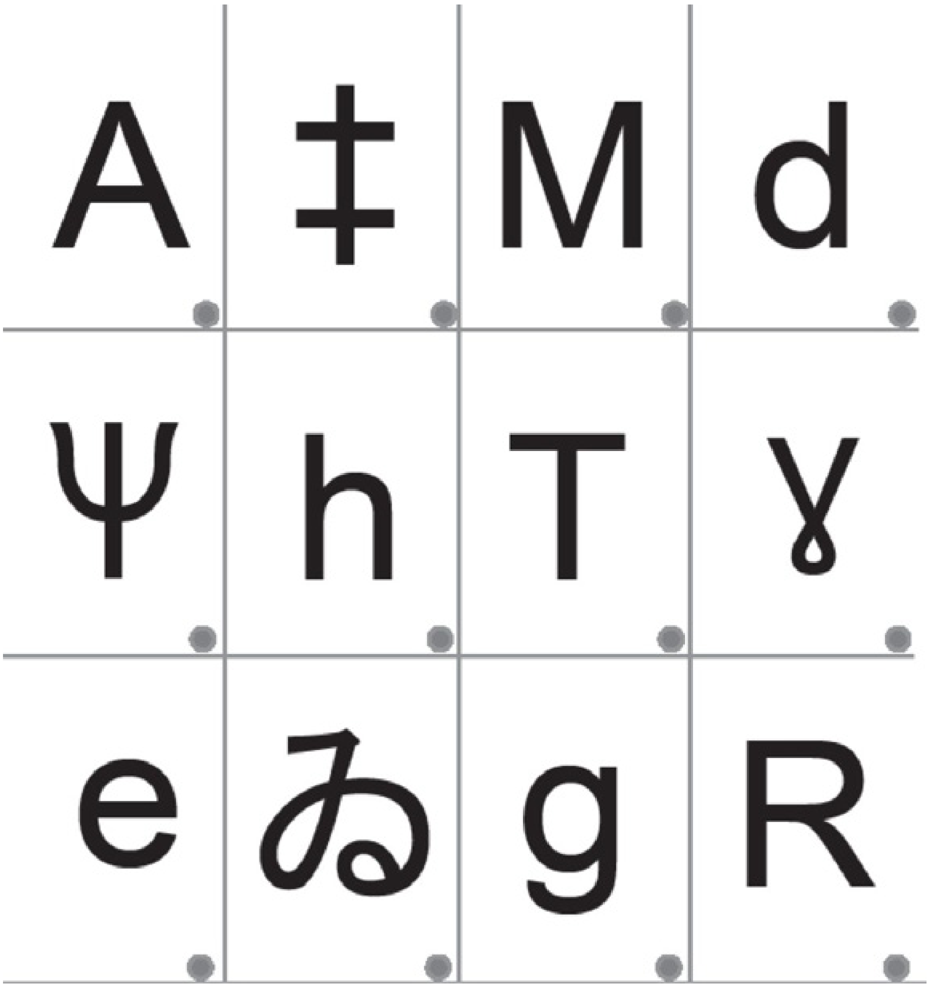
PROSJEKTSLUTT

Prosjektslutt er oppgitt til 31.12.2021. Det fremgår av meldeskjema/informasjonsskriv at dere vil anonymisere datamaterialet ved prosjektslutt. Anonymisering innebærer vanligvis å:

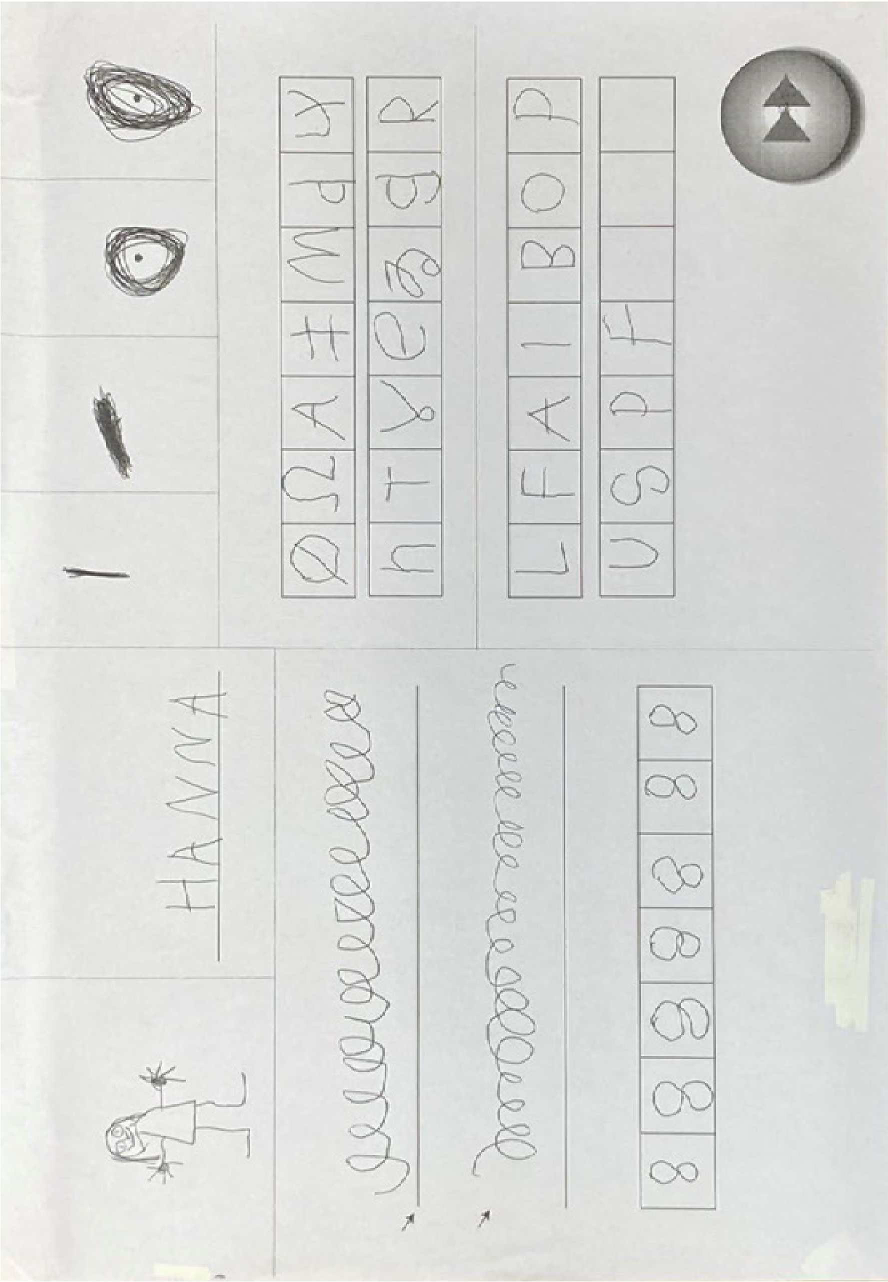
- slette direkte identifiserbare opplysninger som navn, fødselsnummer, koblingsnøkkel
- slette eller omskrive/gruppere indirekte identifiserbare opplysninger som bosted/arbeidssted, alder, kjønn

For en utdypende beskrivelse av anonymisering av personopplysninger, se Datatilsynets veileder: https://www.datatilsynet.no/globalassets/global/regelverk-skjema/veiledere/anonymisering-veileder-041115.pdf

Appendix 3 – Copy task letters and letter-like symbols



Appendix 4 – Test sheet studies 1 and 2



Appendix 5 – Test sheet study 3