Please cite as follows:

Rastle, K. (2017). Writing systems, reading and language. EPS Mid-Career Prize Lecture, presented at the Experimental Psychology Society meeting, July 13, 2017, Reading, England.

<SLIDE 1>

Reading is one of our primary means of gathering and analysing information as we interact with the world.

Reading is so central, so fast, and what I find so remarkable is that it is a learned skill, and a recent cultural invention.

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For thousands of years of human history, nobody could read or write … and then only the most privileged … and even then, this depended on materials innovation; coming up with something to write *on*.

It is only in the past few hundred years that reading has become an activity available to the public.

Reading and writing are learned skills, and sometimes psychologists argue that makes them less interesting than our primary abilities.

But make no mistake, reading and writing dramatically human capability.

In particular, they allow us to make the most of language … to record it … to use it to aide memory … and to transmit it at a far greater speed than would otherwise be possible.

<SLIDE 3>

My journey to understanding how we read began in 1993, when I made one of the great decisions of my life, which was to go to Australia and study with Max Coltheart.

Over next eight wonderful years, built a computer model that we argued reads like people do.

This turned out to be a very successful model. It accounted for many phenomena, and inspired a lot of research.

But as I have grown in the field, I have begun to see limitations of this approach, which I think are important.

One limitation is that this is a static model of a skilled reading system.

My view these days is that if we want to have a full understanding of reading, we need to develop a deep appreciation of what it is that is being learned, and how it is learned.

The DRC model, and other competing models of the time, also conceptualised the problem of reading primarily as one of translating spelling to sound, or reading aloud.

But the problem is that if we define the problem of reading as one of translating spelling to sound, then we miss really important aspects of what written language is communicating.

Finally, at that time, we were not at all interested in how the brain underpins reading behaviour.

I don’t think that this is a failing. But I have been surprised by the consistency of our recent findings regarding reading in the brain… and I feel that we are starting to know enough about reading in the brain that a cognitive psychologist like myself can start to ask interesting new questions about how reading works.

This evening, I am going to talk to you about how I see the problem of reading, and the place that I want to start is with talking about what writing is.

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Writing is an expression of spoken language. But one of the themes I would like to develop is that writing can communicate information that is not in the spoken signal.

In antiquity, writing was indeed seen as a direct representation of spoken language, and texts were always read aloud.

You can see here in the 5th century panel that there were no spaces between words or other graphic conventions… and there was also a very transparent relationship between visual symbols (letters) and sounds.

But slowly these graphic conventions did emerge … spaces between words, punctuation, and experimentation with the visual layout of text.

Palaeographers have highlighted two things about the emergence of these graphic conventions that I find especially revealing.

First, they developed in parallel with the emergence of silent reading.

*The writing* *changed* to make it possible to do something other than just translate the text back to the spoken language.

Note that *these spaces break the link* between written and spoken language… there are no word boundaries in spoken language.

Second, these graphic conventions developed largely in Ireland. Why Ireland?!!

It turns out that these monks, on the frontier, who had embraced Christianity … for these monks, Latin, the language of the Bible, was a foreign language.

The thinking is that these spaces acted as a kind of scaffold to help them learn the spoken language, to learn even the concept of a “word” in the foreign tongue.

These are important insights.

Too often, we see the relationship between reading and spoken language as a one-way street. Reading is parasitic on speech, and writing is an expression of spoken language.

But here we have a case where the written language changed and enhanced the spoken language … and here we have a case where the writing conveys more information than the spoken language. This is a theme that we will come back to.

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The challenge of reading is learning to associate visual symbols with meanings.

Ultimately, the way that this challenge is met depends on the writing system.

Writing systems are all a kind of code for spoken language, but they vary considerably.

Korean is thought to have the most scientifically advanced writing system ever created. The relationship between letters and sounds in the writing system is almost totally transparent, and if you look closely, you can see that the shapes of the symbols themselves are derived from the shape of the articulatory organs during speech. Korean writing therefore provides a *direct line* into spoken language.

The relationship between Chinese characters and sounds is far more opaque, although even among the large number of languages that use the Roman alphabet, there is substantial variation in the transparency with which letters relate to sounds.

The most frequently quoted example is English, where there is often more than one possible pronunciation for a letter, and more than one possible spelling for a sound. This opacity makes English famously difficult to learn to read and spell.

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Politics aside, the point is that reading is a learned skill, and if we want to understand how the brain solves the problem of reading, we have to start with the writing system.

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I’ve spent most of the first half of my career studying reading in English, although I think that I’ve studied it the wrong way around.

That is, it is only now that I am starting to contextualise the empirical findings in terms of the nature of the writing system. If I could go back, I would first seek a deep understanding of the writing system, and let that drive the questions.

English is an alphabetic system, so letters stand for sounds.

But there is high inconsistency between letters and sounds, and indeed, our early modelling work suggested that around 20% of English words have at least one spelling-sound combination that is not predictable.

If we characterise reading as “translating spelling to sound”, then we can stop there.

Indeed, there have been thousands of published papers looking at the problem that irregularity poses for skilled readers … developing readers … how we should teach children about these irregularities … the genetic and neural underpinnings of processing these irregularities.

But if reading is about accessing meaning, then you begin to see something else in the writing system.

Ana Ulicheva, Mark Aronoff and I are developing the hypothesis that the sound-spelling inconsistency in English may actually allow for other regularities to emerge between spelling and meaning.

One example of this trade-off that we’ve known about for a long time is the tendency for the writing system to admit irregular spellings that convey meaningful information. The words ‘magician’ and ‘health’ are not spelled like they sound, but the reason for this is that they contain the words ‘magic’ and ‘heal’, which are very important clues to the meanings of these words. These ‘stems’ occur over and over in the lexicon of English words and have the same meaning.

What has not been so clear previously is that English has a proliferation of spellings for certain sounds, and this allows particular spellings to become *reserved* for particular meanings.

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Take the example of the sound sequence /l@s/ at the end of a word (e.g. necklace, legless). You can see that there are many possible spellings, and this is what makes English so difficult to learn to spell. But only one of these spellings is possible for adjectives. If it is an adjective, then it must be spelled ‘less’. And almost without exception, if it is spelled ‘less’ then it is an adjective.

Let’s look at another example, the sound sequence /Ik@l/ at the end of a word (e.g. nickel, pickle). Once again, there are many possible spellings of this sound sequence. But again, with just a few exceptions, one spelling seems to be *reserved* for adjectives.

One of the most important points to note is that just like the introduction of spacing in the 7th century, this meaningful information is only in the written language. These are all the same sounds, so the spoken language does not disambiguate meaning like the written language does.

What I find really fascinating is that English is one of the only major languages that does not have an academy to regulate its spelling. Unlike Korean, English is old and anarchic … it is always changing, and there is emerging evidence to suggest that it has changed in such a way as to make these kinds of spelling-to-meaning regularities more prominent. We call this ‘morphological’ information.

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I want to give you an illustration of the way that English writing works to help us get to the right meaning of a word.

Why isn’t ‘honour’ spelled this way? Surely, ‘honer’ is a fine spelling of the spoken word.

It is not spelled this way because that spelling would lead you to the wrong interpretation … ‘someone who hones’. –er is an example of one of these chunks that has taken on a particular meaning.

What is interesting is that this was an acceptable spelling for ‘honour’ 500 years ago, but it disappeared when the word ‘hone’ was first used as a verb.

English spelling tries to lead us to the right meaning, and if it doesn’t, then there is evidence that English spelling changes.

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I am going over this material in some detail. I want to make the point that there has been *decades* of work on reading and reading acquisition, across many languages.

But we are only just beginning to scratch the surface of what information is conveyed by the written language being studied. This is very important, because after all, *this is the input* to the reading system!

There is a very big piece of work to do to characterise the information in written language, and to consider the consequences of this for reading and reading acquisition.

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I’ve argued that understanding reading begins with understanding the writing system. And I’ve shown how English spelling conveys information about *sounds and meanings*. So how do we accomplish the reading skill?

Work in my lab has adopted the view that reading is about mapping visual symbols to meanings … and further, that there are two pathways by which skilled readers compute meaning from print. Both of these pathways are underpinned by oral language ability.

One of these pathways is based on translation to the spoken form and then access to meaning, while the other is a direct mapping between printed words and their meanings.

In a recent meta-analysis of neuroimaging data led by Jo Taylor, we have shown that this dual-pathway architecture is also apparent in the brain. The dorsal pathway underpins print-to-sound mapping, and a ventral pathway underpins the print-meaning pathway.

We have been working on the hypothesis that the spelling-sound and the spelling-meaning regularities apparent in the writing system are represented in these two pathways, respectively, in individuals who have acquired the reading skill. In the rest of the talk, I will introduce you to some of this work.

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Decades of work have established the importance of learning the mapping between spelling and sound in reading acquisition in alphabetic writing systems.

That’s why schools in this country use phonics when teaching children to learn to read. Learning the relationship between spelling and sound allows the individual to hook into pre-existing oral language knowledge to acquire the meaning.

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In a recent programme of work with Jo Taylor and Matt Davis, we have been studying the initial stages of reading acquisition in a very detailed way, using a laboratory model in which we teach adults to read novel words printed in unfamiliar scripts, over a period of days or weeks.

Using this laboratory model, we can vary the writing system, the participants’ prior knowledge, or the training protocol. By combining this with fMRI, we can gather detailed measures of the impacts on behavioural performance and neural underpinnings.

When adults are fully trained on an alphabetic writing system like this, you find a pattern of brain activation that is statistically very similar to adults reading actual words in their own language. This is important because it shows that these artificial paradigms provide a valid way of uncovering how we read.

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In one study, we wanted to investigate the impact of learning about spelling-to-sound regularities on reading aloud and comprehension.

Adult participants came into the lab and were trained on an oral vocabulary for two “languages”.

Then, over the course of two weeks, we trained them on the visual forms of these words. You can see that the two ‘languages’ have different shaped symbols, and we presented the languages in a blocked fashion so that participants wouldn’t be confused.

For one language, we emphasised spelling-sound knowledge, and for the other, we emphasised meaning information.

We can see here that when it is hard for participants to recover spelling-sound information (by focusing on whole-word meanings), performance in reading aloud the novel words is impaired, and we see increased neural effort in those same dorsal pathway regions identified in the meta-analysis that we believe represent spelling-sound knowledge.

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Of course, it could be that you are just very good at what you’ve practiced. But that doesn’t turn out to explain these data … because when participants were asked to say the meanings of the novel words (a comprehension task), there was no difference between training conditions. Further, focusing on spelling-sound information did not lead to any neural effort effects in the comprehension task.

Therefore, it seems that learning to read an alphabetic system requires appreciation of the spelling-sound relationship, and we believe that this information becomes represented in the dorsal brain pathway.

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That spelling-sound knowledge gained during reading acquisition remains important in skilled reading.

But what is the nature of that knowledge?

The best way to find that out is to study how people pronounce nonwords. This is an opportunity to assess how the spelling-sound knowledge that adults have encoded over years of experience with the writing system is brought to the problem of pronouncing letter strings that people haven’t seen before.

This is exactly what we did in a recent mega-study led by Betty Mousikou, in which 41 adults read aloud 915 disyllabic nonwords like these. We then transcribed the resulting 37,515 nonword pronunciations.

Unsurprisingly, there is variability in how people read these.

The nonwords generated up to 22 different pronunciations, and the colours on this graph indicate the frequency of each alternative response.

This looks like a mess.

But it turns out that this variation is strongly attributable to spelling-sound regularities in the writing system.

If we think about pronunciation variability for any one item, the strongest predictor of that variability is the consistency of the spelling-to-sound mapping for the units that nonword contains.

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Let me give you a couple of examples.

BAMPER was an item that got only one pronunciation across the whole sample. If we take the onset and rime units in each syllable, and look at how those units are pronounced in all of the words that contain those units, you can see that there is very little variation. These percentages represent how often the most frequent pronunciation is used across words in the lexicon.

In contrast, ELUCH is an item that got 22 pronunciations across the whole sample. If we split this into its syllables, and look at the consistency of its onset and rime units, the picture is much different. Thus, the constituent units in ELUCH are far less consistent across the words that people know, and this is reflected in inter-subject variation.

The same type of analysis can be done for stress, where again, the most important predictor of stress certainty across participants is the consistency with which particular letters map to stress patterns in the dictionary.

In the case of BAMPER, all subjects stressed the first syllable. When we look at those units again, what we find is that that words containing those units are almost always stressed on the first syllable. The situation is very different for ELUCH. Here, words containing ‘e’ as the rime of the first syllable are only rarely stress on the first syllable, but words containing these units in the second syllable are typically stressed on the first. In turn, our subjects were split 50/50 on how they stressed this nonword.

Of course, it could be that each individual participant is very certain of the relationship between spelling and sound, but that the knowledge of individual participants varies. But this doesn’t seem to be the case, as we’ve observed similar effects *within* individuals. Participants are internally inconsistent, in a way that reflects the strength of the spelling-sound mapping across the lexicon.

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To sum up, it appears that the characteristics of the writing system that people have learned are reflected in adults’ stored knowledge of the relationship between spelling and sound.

English is inconsistent in terms of the relationship between spelling and sound, and this is portrayed in the way that people read nonwords.

It is also important to note that even for adults with 16, 17, 18 years of experience with the writing system, there are areas of the spelling-sound relationship about which there is considerable uncertainty.

That turns out to have important implications for our understanding of skilled English reading.

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To summarise,

I have argued that learning to appreciate the spelling-to-sound mapping is critical in learning to read an alphabetic writing system … these are the primary regularities … and we’ve been able to simulate this when adults learn to read in an artificial writing system.

We believe that this information is represented in the dorsal brain pathway, and we’ve shown this via a meta-analysis of skilled reading, and in a laboratory acquisition task.

When we look at skilled readers, we find that the strength of spelling-sound relationships in the writing system is reflected in the spelling-sound knowledge that adults use to read nonwords aloud. Adults’ knowledge is a mirror of the writing system.

Finally, even after decades of work, I think that there is still a question over the extent to which spelling-sound knowledge can support skilled, English reading. For many years, researchers argued that this knowledge plays a ‘leading’ role in the computation of meaning, but with the uncertainty we have seen even in adults with many years of experience, I do not believe that this argument holds.

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We have seen that the acquisition of print-sound knowledge is necessary in reading acquisition in alphabetic writing systems, and that the strength of the spelling-sound mapping is reflected in skilled readers’ knowledge.

However, certainly in a writing system like English in which the spelling-sound mapping is relatively opaque, and in which there are many homophones, it is unlikely that this knowledge alone can drive skilled reading.

Instead, I and others have argued that skilled readers also require rapid word recognition ability, directly from print. The recent meta-analysis led by Jo Taylor suggests that this form of knowledge is underpinned by the ventral reading pathway.

This is really about developing reading expertise … about the accumulation of experience with written language over many years … and very little is known about how it arises.

One piece of work that I find particularly inspiring is that of Michal Ben-Shachar and colleagues from Stanford. In a major longitudinal study, they found that the ventral pathway is still changing in sensitivity into adolescence, even for simple words. This changes our understanding of reading acquisition … we really need to be thinking about it taking 10 years to learn to read.

We don’t tend to study children in this age range, but there is no reason that the reading skill should not continue to be refined as we get older. Indeed, we know from Brysbaert’s mammoth mega-study involving over 200,000 participants that the number of words that people can recognize from print grows substantially between the ages of 20 and 60, and that people show particularly rapid growth in periods of adult education.

For example, for those with PhD training, you can see the very rapid growth within those years of actual study.

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Most of the research on the development of reading expertise along this pathway has been concerned with item-level effects – the journey of a particular word into one that a child can recognize rapidly. People have called this “orthographic learning”, and one of our symposium speakers earlier (Kate Nation) has proposed an influential theory of how this arises.

But I have been interested in a more global question -- the way that the regularities between spelling and meaning that I described earlier bear on this.

If we think about learning to recognize each English word and map it to its meaning, then the challenge of doing that is dramatically reduced if your representation of print is organised along morphological lines, as shown in this example.

In fact, in a recent study Brysbaert and colleagues estimated that the average 20 year old recognizes around 71000 words, but that number decreases if inflections like “develops”, “developing”, “developed” are removed, and it decreases further to just 11,100 base words if derivations like the rest of these are removed.

In this example, these 15 separate exemplars are all pretty much the same word. The challenge of learning to recognize them is dramatically reduced if we can count them as just one word.

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But only way that we can understand that these are all part of the same base word is that we know that the letters at the beginnings and endings are somehow significant, and modify the base word.

This is where the writing system becomes very important. The large number of spellings in English for particular sound sequences – the characteristic that makes English opaque along spelling-sound lines -- means that some spellings can become *reserved* as affixes.

So, what I’m arguing is that the structure of the writing system helps us to organise orthographic representations in such a way to permit rapid access to meaning.

The question I’ve been interested in is, how do we represent that morphological knowledge and how is it learned?

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I started work on this question about 20 years ago now, when I made another of the great decisions of my life, which was to come to work with Lolly Tyler and William Marslen-Wilson as a postdoc. William and Lolly caused me to think more broadly about language.

We were interested at that time in whether skilled readers analyse morphemic information, and the speed with which they do that.

We conducted a set of priming experiments in which we compared morphological priming to semantic priming, and we varied the duration of prime, so that in the shortest case the prime was masked and not available for conscious report.

We found very strong morphological effects which could not be ascribed to semantic similarity. Moreover, we found what is now frequently reported, that semantic priming effects do not arise at the shortest prime durations.

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In this experiment, we also included items like corner-CORN which look like they could be morphologically related, but which aren’t.

We didn’t anticipate that we would find any priming for such items.

I remember that it was very difficult at the time to find items like this. Of course, now, I know why that is … it is because the writing system doesn’t like these items. In these cases, you would normally have a different spelling of that sound sequence (something like cornyr … just like in the ‘honour’ example). Words like ‘corner’ are the true exceptions.

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Well, we found against expectation that under unconscious presentation conditions, these items behaved like real morphological items.

Of course, this could just be because they share letters, and that is what is yielding the priming effect. This was really the beginning of my long collaboration with Matt Davis, who was also working in the lab at that time.

In a programme of work over the next 10 years, and involving multiple replications, we showed that these very strong priming effects arise whenever items \*appear\* to be morphologically related. These effects do not arise just on the basis of shared letters, as in shovel and shove.

It seemed to us that skilled readers had discovered something about the spelling-to-meaning regularity of affixes, and were applying this indiscriminately to all items with an apparent morphological structure.

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In more recent work, working with Aureliu Lavric and later Davide Crepaldi, we’ve used ERPs to develop a temporal characterisation of these processes.

In this particular study, we looked at unprimed recognition of printed words like ‘shovel’ (which cannot be parsed into morphemes), ‘teacher’ (which has a genuine morphological relationship with ‘teach’), and ‘corner’ (which looks morphologically structured but is not).

If we look at the waveforms, what you can see around 190ms is attenuation for the two morphologically-structured conditions. Those conditions are different from the non-morphological condition. We ascribe this to an analysis based on *apparent* morphological structure.

Around 60 ms later, we see a substantial positivity for these items like ‘corner’, which we ascribe to a semantic analysis or integration process, when it would become apparent that a morphological analysis led to the wrong outcome.

To summarise, skilled adults readers analyse words in terms of spelling-meaning regularities very rapidly. This analysis can be rapid because it is superficial, based only on the *apparent* presence of morphological structure. Finally, this analysis can be superficial because of the writing system … the fact that the writing system does not favour words like ‘corner’. These end up being spelled another way.

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In more recent work, we have asked the question “How do we acquire representations that permit us to conduct this superficial analysis?”

We’ve taken two approaches.

The first involves interrogating the spelling-meaning knowledge of skilled readers. Specifically, we are looking at the consistency with which suffixes map to particular functions … so in this example, ‘-ness’ has the same function in all of these words. We’ve found that skilled readers’ knowledge of spelling-meaning regularities mirrors the consistency with which groups of letters map to grammatical class. I encourage you to attend Ana Ulicheva’s talk tomorrow where you can hear more about this work.

The second involves looking at the fundamental constraints on acquiring this knowledge in laboratory acquisition studies. Just as in the studies of skilled adult readers, here again, we’ve looked at how the consistency of the mapping between spelling and meaning impacts on learning. We’ve also looked at the impact of contextual diversity, that is, the extent to which a spelling-meaning association surfaces across a range of different stems. For example, ‘-ness’ has the same function across many different words.

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In Jakke’s experiments, adults come into the lab, and are required to learn new novel vocabularies. Unknown to the participants, the novel words have a morphological structure. In this example, -nule, the new suffix is paired with a range of different stems. These novel words all have definitions, and across the whole set, it becomes clear that –nule has a particular function. For example, these words might all refer to some kind of agent.

In this particular experiment, adults learned vocabularies when the novel words were paired with eight different stems, or when the novel words were paired with just two different stems. In this low-diversity context, the stems were just repeated over and over, four times as often as in the other condition.

Participants then come back a week later for testing. We test them using a sentence priming task, like the following. They get a sentence frame like ‘The manager often argued with the …’, and then following a button press, participants are required to read aloud a word that appears on screen. This word has the same morphological structure as novel words studied earlier, but is not an item that they’ve seen before. We figured that if participants had learned something about the meaning of ‘-nule’, then they might show a sentence priming effect. That is, they would be faster to read aloud target words when those targets appeared in congruent contexts rather than incongruent ones. In this case, the target ‘drinknule’ is congruent with this first sentence, because –nule is a person, and you can argue with a person. But the target ‘printnule’ is incongruent with this second sentence, because you can’t sneak into a person.

What you can see in the sentence priming data is that when the novel affixes were paired with a large number of stems, a robust sentence priming effect emerged. But when they were paired with just two stems, no sentence priming was apparent.

What this suggests is that spelling-meaning regularities have to occur across multiple contexts in order to be learned.

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In a second experiment, we tested the impact of the consistency of the spelling-meaning relationship on learning. In one condition, participants learned novel affixes paired with eight stems as before, with the affix having the same function across all stems. In the other condition, participants learned the novel affixes with eight stems, but where half of the items indicated one meaning for the affix, and where the other half indicated another meaning.

If we look at the sentence priming data, you see that we replicate the previous findings when the novel affix has a consistent meaning across all contexts. But no sentence priming effects emerge where there was inconsistency in the spelling-meaning mapping.

These data suggest that a consistent association between spelling and meaning is critical for learning these units.

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To summarise, the data indicate that we acquire knowledge of spellings that consistently signify particular meanings, and that do so repeatedly in combination with known stems. We believe that the strength of the spelling-meaning relationship for particular units is mirrored in skilled adult readers.

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Finally, I’ve argued that acquiring morphological knowledge underpins development of the ventral print-meaning mapping, but I haven’t yet presented any evidence for this.

In new DTI imaging work with Michal Ben-Shachar’s lab, we’ve begun to tie morphological knowledge to diffusion properties of the ventral reading pathway.

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We measured 45 adults’ sensitivity to morphological knowledge using a behavioural task designed by Davide Crepaldi.

We then looked for a relationship between this behavioural measure of sensitivity and diffusion properties of fibre tracts in the ventral and dorsal pathways pictured here.

This relationship was apparent in all ventral tracts (mostly in the left hemisphere), and not in the dorsal tracts. Further analysis showed the relationship holds even after controlling for phonological ability.

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For any of you who are interested in this type of analysis, the associations between sensitivity to morphemes and the ventral stream tracts emerged on both fractional anisotropy and mean diffusivity measures. Both of these were driven by radial diffusivity rather than axial diffusivity.

The direction is that people more sensitive to morpheme showed greater radial diffusivity, possibly indicating wider axons or greater pruning.

In general terms, while we cannot draw any causal inferences from these data, what we can say is that it looks like morphological knowledge is associated with diffusion properties of ventral white matter pathways, mostly in left hemisphere.

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I am coming to the end of my time, so I want to conclude with a few points.

First, I’ve argued that understanding reading starts with the writing system. Written language is an expression of spoken language, but it communicates different information … and we’ve seen examples of how writing has *changed* to support skilled reading.

Second, I’ve argued that English writing comprises spelling-sound and spelling-meaning regularities. I’ve also made the case that spelling-meaning regularities are a *consequence* of spelling-sound irregularity.

Third, I’ve argued that spelling-sound knowledge represented in the dorsal brain pathway is critical in reading acquisition, and that the nature of this mapping is mirrored in skilled readers. But I’ve also argued that the uncertainties within this mapping mean that it cannot support skilled reading.

Fourth, I’ve argued that spelling-meaning regularities in the writing system are reflected in skilled readers’ knowledge. I’ve argued that this information is represented in the ventral brain pathway, and that it is critical for rapid access to meaning.

Finally, I want to end by reflecting that for many years, our field was fractionated between people studying skilled reading, people studying reading development in young children, and we were almost completely isolated from research on memory and learning. But that is all beginning to change, and that is something I find very exciting.

Reading is really all about acquiring item specific and general knowledge from the accumulation of experiences with a writing system, sometimes over many years. So, I look forward to spending the next half of my career having conversations within the intersections of these various research areas.

<FINAL SLIDES>