Supplemental Material to Polymeric foam pressure-sensing pens for measuring written language production

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Supplementary to Results:

Pressure ranges in handgrip

Pressure exerted during writing is variable due to pauses in writing, small changes in grip, and endogenous changes in grip forces. Across 16 participants, the average median absolute deviation for pressure during writing was 17.48 kPa. Pressure variability differed across participants with a minimum median absolute deviation of 7.52 kPa. Variability in grip pressure during writing, as measured using median absolute deviation, was statistically indistinguishable between the two pens, although it was numerically lower for participants using the prototype I (plastic grip) than for those using prototype II (rubber grip, Fig. S1). However, these difference were not found to be statistically significant using a one-way analysis of variance (prototype I: 15.51 kPa, prototype II: 19.44 kPa; F(1,15) = 1.194, p=0.29; $\eta_p^2 = 0.03$).

Reaction Times

To characterise the effect of the four conditions on reaction time in the Y/N task, we fitted a linear mixed-effect model to predict reaction time using lme4 (Bates et al., 2015). Random effects structure was determined by dropping effects with non-significant variance in accordance with Barr et al., 2015. We then used nested model comparison to determine significance values for fixed effects. The model included stimulus difficulty (easy/hard), word status (word/non-word), and the interaction of these two features as fixed effects. All variables are dummy coded with hard, non-words as the baseline. Random intercepts were included for individual writers and stimuli. As predicted, there was an interaction effect between word status and difficulty, with greater differences in reaction times between easy and hard trials in word trials compared to the non-word trials (β=0.32, SE=0.15, χ^2(1)=4.54, p=0.03). Reaction times were faster in easy relative to hard trials (β=-0.28, SE=0.10, χ^2(1)=13.82, p<0.001). While reaction times were numerically faster in word trials relative to non-word trials, there was no significant main effect of word status, (β=-0.28, SE=0.10, χ^2(1)=2.3968, p=0.12).

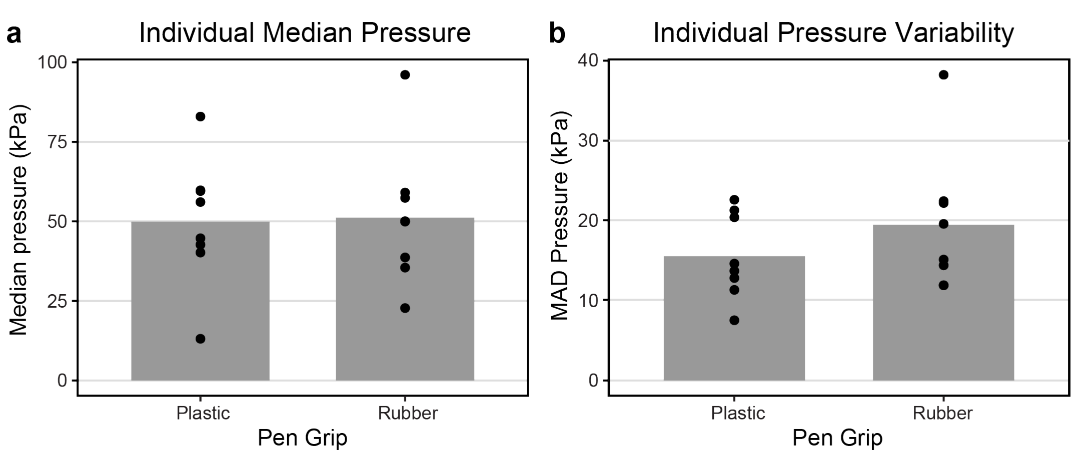


Figure S1. Comparison of participant median pressure and median absolute deviation across pen grip types. Bars represent mean across participants. Points represent individual participant values.

The same procedure was followed to characterize data collected in the OMR task. In the case of the OMR task, the random effects structure of writer and stimulus intercepts was supplemented by a random slope of word status in the writer variable. Here, there was no significant interaction between difficulty and word status in predicting reaction time at the alpha-level of 0.05 (β=0.38, SE=0.20, $\chi^2(1)$=3.39, p=0.07). As in the Y/N task, there were longer reaction times in hard trials relative to easy trials (β=0.17, SE=0.14, $\chi^2(1)$=10.47, p=0.001). There was no significant main effect of word status despite reaction time being numerically faster in words than non-words (β=-0.41, SE=0.16, $\chi^2(1)$=2.57, p=0.11).

Pressure data

To quantitatively inspect this pattern, we calculated the mean increase in pressure over baseline (P_d) during the lexical decision period in all trials. The role of the difficulty and word status conditions was then investigated using model comparison with linear mixed-effects models.

We used the same procedure described for reaction time analysis to fit linear mixed-effects models to analyze P_d. Fixed effects included word status, difficulty, and the interaction of these two features. Random intercepts were fitted for writer and stimulus. There was a significant interaction between word status and difficulty, with the difference in P_d between hard and easy trials more salient in the word trials than the non-word trials (β=3.05, SE=1.05, $\chi^2(1)$=5.36, p=0.02). Word trials also produced greater than P_d non-word trials (β=3.21, SE=0.74, $\chi^2(1)$=8.11, p=0.004) and easy trials showed greater P_d than hard trials (β=0.15, SE = 0.73, $\chi^2(1)$=5.46, p=0.02).

An identical procedure was followed to analyse P_d in the OMR task.The random effects structure of writer and stimulus intercepts was supplemented by a random slope of word status in the writer variable. There was a greater effect of difficulty in the word versus non-word trials (β=-2.38, SE=1.04, $\chi^2(1)$=4.98, p=0.03). Hard trials were produced with lower P_d than easy trials (β=-1.14, SE=0.74, $\chi^2(1)$=15.19, p<0.001). While there was numerically greater P_d measured in word trials than non-word trials, the main effect of word status did not reach significance at an alpha level of 0.05 (β=2.51, SE=0.82, $\chi^2(1)$=3.41, p=0.06).

Supplementary to Methods:

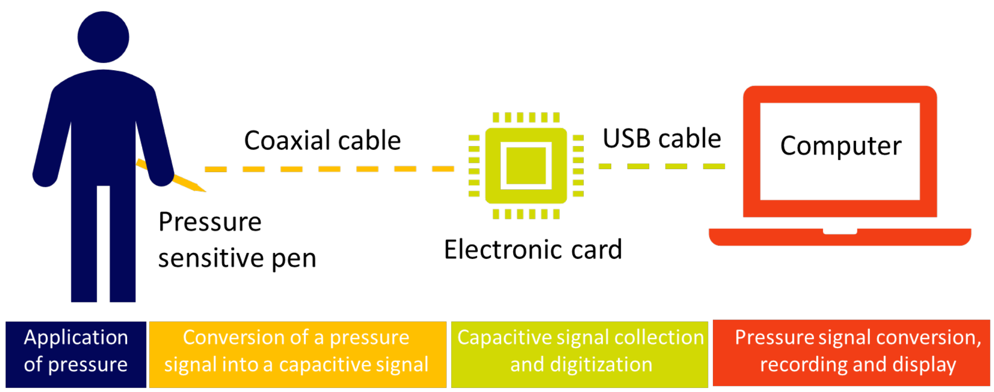


Figure S2. Block diagram of the experimental setup.

Optimizing ergonomic design and signal acquisition.

To empirically determine a typical range of handwriting grip pressure, we analysed data collected during a prototypical writing task: text copying with and without an additional mental load task (remembering a 7 digit number). The average mean pressure during the copying task across participants is 20.5 kPa. However, typical pressure values differ widely across individuals, with a minimum median pressure of 13.1 kPa and a maximum median pressure of 96.0 kPa across writing. The variability in participant pressure ranges demonstrates the need to calibrate pressure sensing pens to be highly sensitive in a range centered around 50 kPa, but with moderate sensitivity at least as low as 10 kpa and as high as 150 kpa in order to capture the full range of less typical writers. There was no significant difference in the group mean of median pressure values performed by individuals who used the plastic versus the rubber grip pens as determined by a one-way analysis of variance ($F(1,15) = 0.015$, $p = 0.90$; $\eta_p^2 < 0.001$; Fig.S1).

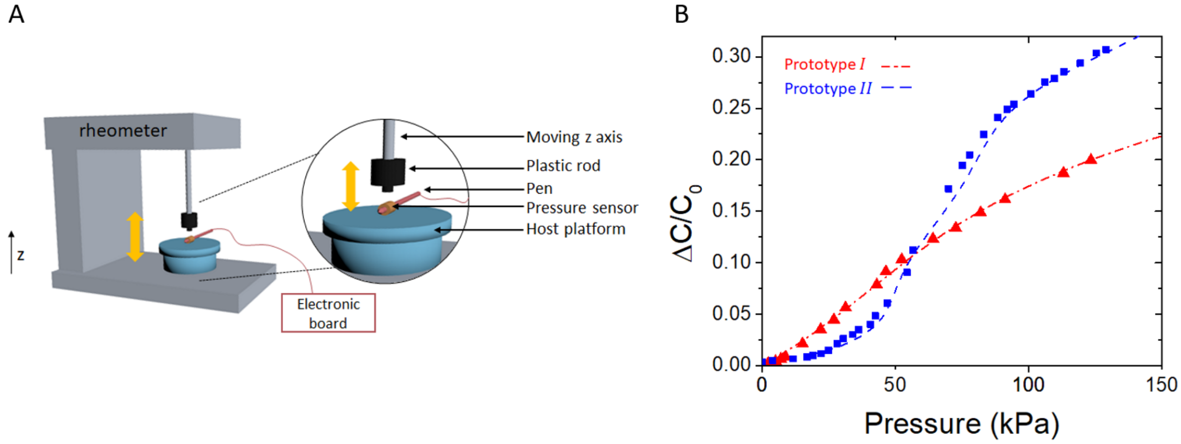


Figure S3. A) Schematic representation of the set-up for measuring calibration curves. B) Capacitance variation as a function of the applied pressure. Red top triangles and blue squares are calibration measurements. Blue dash line ($P = -4,8 \cdot 10^6(\frac{\Delta C}{C_0})^6 - 5.1 \cdot 10^6(\frac{\Delta C}{C_0})^5 - 2.1 \cdot 10^6(\frac{\Delta C}{C_0})^4 + 4.2 \cdot 10^5(\frac{\Delta C}{C_0})^3 - 4.2 \cdot 10^4(\frac{\Delta C}{C_0})^2 + 2.2 \cdot 10^3(\frac{\Delta C}{C_0})$) and red dash dot line ($P = 1.2 \cdot 10^4(\frac{\Delta C}{C_0})^3 - 2.7 \cdot 10^3(\frac{\Delta C}{C_0})^2 + 6.8 \cdot 10^2(\frac{\Delta C}{C_0})$) represent polynomial fits.

Supplemental information on pressure sensors.

The size of the pressure sensors is 0.5 cm^2. To make them, a flexible copper electrode was deposited on a plastic substrate and then the sensitive material is directly deposited on it. Liquid PDMS is deposited to attach the material to the electrode, and cross-linked around the material (1h, 60°C). Then the upper copper electrode is deposited on the material and fixed by a last layer of cross-linked PDMS allowing the total maintenance of the structure, it is this last layer which will be in contact with the finger. For capacitance measurement, a coaxial cable connects the two electrodes. The sensor thus formed is attached to the pen with double-sided tape and the coaxial cable is fed in at the pen tip, and out at the end.

Calibration and signal conversion.

The data are directly transmitted and stored on a computer. Data are processed (i.e. conversion of capacitances to pressures regarding the calibration curve), recorded, and displayed using Matlab software. To obtain calibration curves (Fig. S3), we applied a well-controlled load by a rheometer (Discovery HR-2, TA Instruments), used as mechanized z-axis stage and force gauge (Fig.S3, A). A top plastic rod (same surface than the sensor) was connected to the z-axis stage while the sensor, already integrated into the pen, is fixed to the host platform. The rheometer applies linear loading–unloading cycles to the sensor. At the same time, the capacitances are measured using the previously described electronic board.

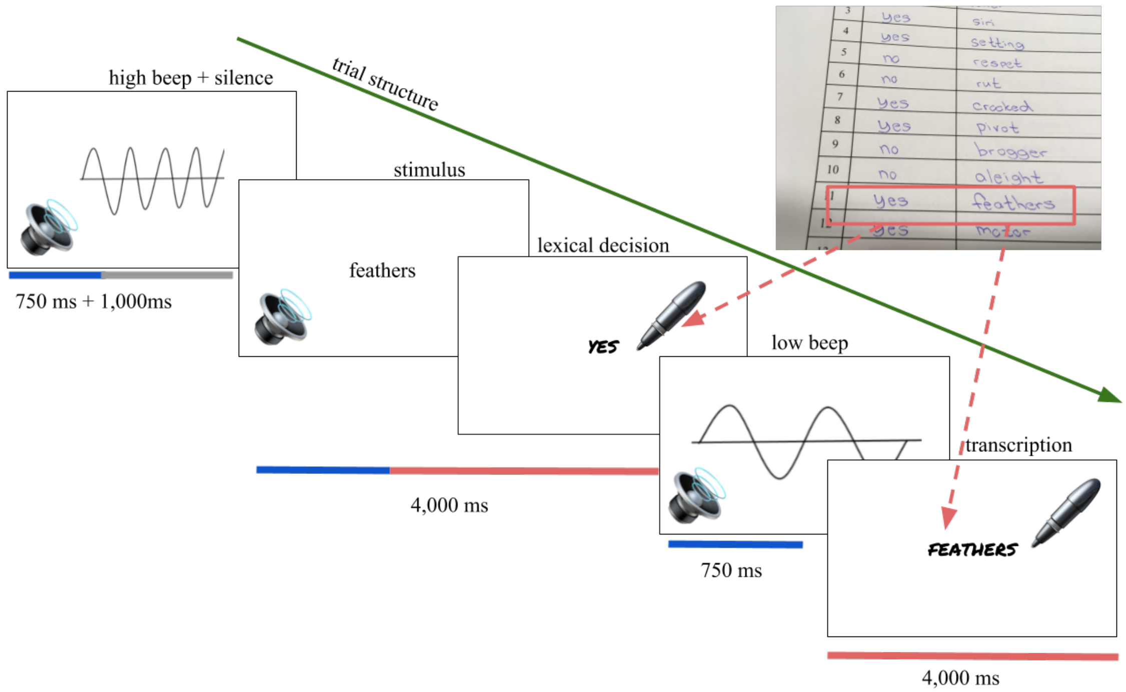
Fig.S3B shows the relative capacitance variation of the sensor as a function of the applied pressure (from 0 to 150 kPa). The mathematical model of the calibration curve with a polynomial fit provides an equation which allows the conversion of a capacitance signal into a pressure signal. This model is used by Matlab to convert the digital signals it receives into pressure values.

Experiments A and B
Stimuli used

2-syllable Words				2-Syllable Non-Words			
easiest	RT	most difficult	RT	easiest	RT	most difficult	RT
setting	425.5	*shirtfront*	1987.8	*dyemen*	700.7	*incuse*	1671.9
respects	474.0	*abut*	1886.0	*breshing*	701.0	*sandhuck*	1555.1
motor	485.5	*wielder*	1835.5	*brager*	725.6	*brigage*	1546.5
feather	497.3	*simplex*	1788.0	*ezbit*	735.0	*dispasse*	1565.4
turrmoil	508.5	*alight*	1750.0	*mellul*	741.8	*steeree*	1510.1
prevail	516.3	*adjure*	1635.3	*ertes*	742.5	*bentras*	1503.2
eggshell	529.3	*surely*	1713.8	*lownter*	745.7	*hyrus*	1501.2
husbands	531.5	*gangland*	1713.4	*pivid*	765.2	*inbowsts*	1499.8
bumping	532.3	*airsick*	1669.5	*bypus*	767.3	*weektly*	1486.8
crooked	540.3	*spoilsport*	1689.3	*wowner*	776.7	*booskick*	1478.8
brewers	540.8	*couplers*	1676.8	*fifful*	777.7	*cunscrone*	1476.1
loophole	549.8	*aground*	1676.5	*playcleanse*	779.2	*athoud*	1465.5
Average RT	**510.9**		**1751.8**		**746.5**		**1521.7**
Maximum RT	**549.8**		**1987.8**		**779.2**		**1671.9**
Minimum RT	**425.5**		**1635.3**		**700.7**		**1465.5**

Table 1. List of stimuli used; Reaction Times (RT) from MALD (Tucker et al., 2019). Non-words show one of several possible spellings for each item.

Overview of paradigms.



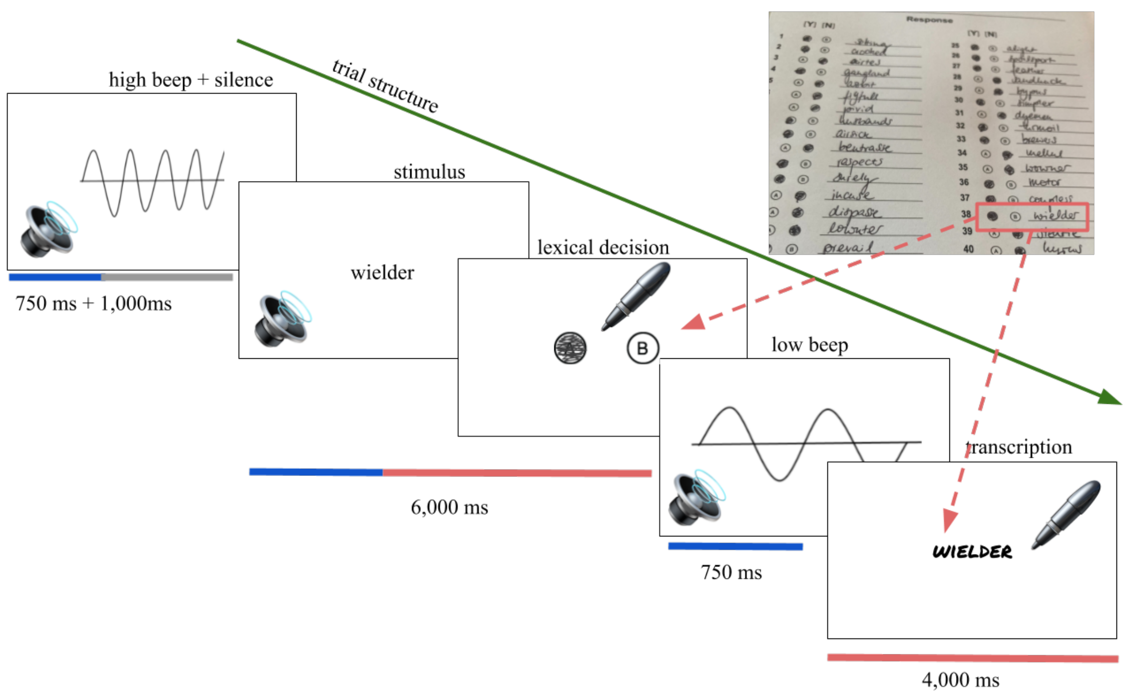


Figure S4. Diagrams of lexical decision time procedures, Experiment A (above), Experiment B (below).