The polyadenylation landscape after *in vivo* long-term potentiation in the rat brain

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Highlights

• The dynamics of poly(A) tail length in hippocampus following LTP is mainly related to the transcriptional induction

• Chemical stimulation *in vitro* leads to poly(A) tail shortening in synaptoneurosomes

• LTP-induced changes in polyadenylation site usage affect several mRNAs in hippocampus

• Transcripts with semi-templated poly(A) tails are involved in synapse physiology

Summary

Local protein synthesis in neurons is vital for synaptic plasticity, yet the regulatory mechanisms, particularly cytoplasmic polyadenylation, are not fully understood. This study employed nanopore sequencing to examine transcriptomic responses in rat hippocampi during *in vivo* long-term potentiation (LTP) and in synaptoneurosomes after *in vitro* stimulation. Our long-read transcriptomic dataset allows for detailed analysis of mRNA 3′-ends, poly(A) tail lengths, and composition. We observed dynamic shifts in polyadenylation site preference post-LTP induction, with significant poly(A) tail lengthening restricted to transcriptionally induced mRNAs. Poly(A) tails of these genes showed increased non-adenosine abundance. In synaptoneurosomes, chemical stimulation led to shortening of poly(A) tails on preexisting mRNAs, indicating translation-induced deadenylation. Additionally, we discovered a group of neuronal transcripts abundant in non-adenosine residues poly(A) tails. These tails are semi-templated and derived from extremely adenosine-rich 3′UTRs. This study provides a comprehensive overview of mRNA 3′-end dynamics during LTP, offering insights into post-transcriptional regulation in neuronal activation.

Keywords

long-term potentiation, rat brain, dentate gyrus, synaptoneurosomes, nanopore direct RNA sequencing, nanopore cDNA sequencing, polyadenylation, non-adenosine, poly(A) tail

Introduction

Synaptic plasticity, the activity-dependent modification of synaptic efficacy, is critical for learning and memory processes[1]. It is divided into several paradigms, with the long-term potentiation (LTP) and long-term depression (LTD) being the primary models for synaptic strengthening and weakening, respectively. LTP has early and late phases, distinguished by their duration and underlying mechanisms. Early-phase LTP involves the activation of signal transduction pathways that modulate calcium-sensitive kinases. This enhances AMPA receptor conductance and leads to an increased number of AMPA receptors at the postsynaptic density (PSD) through exocytosis. Late-phase LTP, on the other hand, involves gene expression and *de novo* protein synthesis, which facilitate dendritic spine growth and PSD restructuring.

Pre-mRNA polyadenylation is a 3′-end processing mechanism for the export of RNAs from the nucleus into the cytoplasm. It contributes to mRNA stability and thus acts as a master regulator of gene expression in eukaryotes [2]. The polyadenosine tail, synthesized by the

canonical poly(A) polymerase at the poly(A) site (PAS), is defined by upstream and downstream *cis*-regulatory elements recognized by the cleavage and polyadenylation specificity factor [3–5]. Most mammalian genes contain multiple PASs, leading to multiple mRNA isoforms [6]. In neurons, local translation of mRNAs in dendrites and axons enables the rapid delivery of proteins involved in the regulation of synaptic maintenance, homeostasis and plasticity [7]. The interplay between alternative polyadenylation sites (APA) defining 3′UTRs, poly(A) tail length, translation, and mRNA decay is fundamental in gene expression regulation. Indeed, translational efficiency, as well as mRNA half-lives have been shown to vary more than 1,000-fold between individual transcripts, demonstrating the range and specificity of the regulation of mRNA stability and abundance [8]. Several years ago, it was postulated that the translation of a specific group of mRNAs is activated by cytoplasmic polyadenylation [9,10]. These transcripts have specific sequence motifs bound by CPEB proteins which initially induce deadenylation to store dormant mRNAs having short poly(A) tails. Upon stimulation, poly(A) tails are then extended to activate translation. In addition to polyadenylation, several other post-transcriptional regulatory mechanisms can regulate local protein synthesis including microRNAs or pathways that influence the activity of translation factors [11–15].

Despite the long-standing interest in poly(A) tails and the regulation of protein synthesis, methods for reliable, genome-wide estimation of poly(A) tail length have only recently been developed [16]. Initially, most studies relied on Illumina-based protocols, such as TAIL-seq and PAL-seq [17,18]. However, DNA polymerase is unable to properly bind to long homopolymeric tracts (repetitive sequences) during PCR amplification, resulting in truncated estimates of poly(A) tail length. In addition, these methods require RNA fragmentation, as the sequencer can only read 200-300 base pairs at a time [16].

Third-generation PacBio sequencing protocols, such as FLAMseq and PAIso-Seq, eliminate the upper limits of poly(A) tail length detection and provide a complete overview of the entire mRNA molecule [19,20]. However, they are still affected by amplification bias from library preparation, which calls into question the reliability of the results. Oxford Nanopore Technologies (ONT) offers a solution with its nanopore direct RNA sequencing (DRS) protocol. Unlike previous methods of poly(A) tail length measurement, DRS does not require amplification, allowing for real-time sequencing of single RNA molecules and generating full-length, strand-specific reads [21,22]. This approach provides the most reliable poly(A) tail length estimations and, with our recently developed algorithm Ninetails (https://github.com/LRB-IIMCB/ninetails), can also analyze nucleotide composition [23].

Additionally, long reads facilitate the study of other aspects of mRNA regulation, such as PASs usage [24].

Here we used nanopore DRS and cDNA sequencing to examine changes in expression and in poly(A) tail characteristics following LTP induction in the rat dentate gyrus *in vivo*. Our data provide first such a rich long-read transcriptomic resource and enables us to assess the dynamics of the 3′-ends of mRNAs during LTP. First, we have shown that a few genes are differentially expressed as early as 10 min after LTP induction, and that these changes are even more pronounced 60 min post-LTP induction. While a few transcripts have an elongated poly(A) tail 10 min post-stimulation, a more prominent change was observed at 60 min, including both elongation and shortening. Second, we noticed a general tendency toward shortening of the 3′UTRs for both time points post-stimulation among all reported alternative polyadenylation events. Third, among the differentially expressed mRNAs, we observed an elevated proportion of poly(A) tails with non-adenosine residue insertions. We also found a specific group of neuronal mRNAs abundant in non-adenosines in their poly(A) tails. However, these possess extremely adenosine-rich 3′UTRs, suggesting that these tails are semi-templated. Finally, using the synaptoneurosome preparations, we show that the regulation of synaptic mRNA translation appears to be uncoupled from polyadenylation.

Results

Nanopore sequencing reveals expected changes in gene expression following LTP induction

To study the activity-induced changes in post-transcriptional regulatory programs in neurons, we used LTP in the rat dentate gyrus as an established *in vivo* model for synaptic plasticity. Short bursts of high-frequency stimulation (HFS) were applied to one hemisphere (ipsilateral DG), while the unstimulated hemisphere (contralateral DG) served as a control (Figure 1A). HFS of the medial perforant path input to DG (Figure 1B) resulted in a rapid and stable potentiation of the field excitatory postsynaptic potential (fEPSP) slope: 57+/-13% for 10 min and 55+/-7% for 60 min (Figure 1C). The increase in the fEPSP slope is accompanied by a rise in population spike amplitude (Figure 1C insert). Then, after *in vivo* LTP induction (10 and 60 min), both ipsi- and contralateral dentate gyri were dissected for RNA extraction. Since successful LTP induction leads to the expression of immediate early genes (IEGs) such as *Arc* and *Fos* [25–30], we only analyzed the samples with increased expression of these markers in the ipsilateral hemisphere (Supplementary Figure 1).

To investigate the transcriptomic changes induced by neuronal activity after *in vivo* HFS, we applied two different nanopore sequencing approaches: Nanopore Direct RNA Sequencing (DRS) and Nanopore cDNA from Oxford Nanopore Technologies (ONT). Both methods produce reads that encompass whole molecules of interest, overcoming the limitations of Illumina [24]. In particular, DRS provides insights into the mRNA inventory without a synthetic proxy, avoiding amplification bias [16,22], whereas cDNA sequencing yields higher coverage, ensuring that sufficient data is available for less expressed genes [31,32]. With DRS, we obtained an average of 0.5 million reads per sample/run, while with cDNA sequencing we obtained about 15 million reads per sample/run, which met the requirements of the analysis. DRS on ipsi- and contralateral dentate gyri confirmed HFS-dependent induction of IEGs (including *Arc* and *Fos* as well as many others) in agreement with the qPCR data (Figure 1D; Supplementary Figure 1). The 10 min post-HFS time point was chosen because we wanted to compare the mRNA polyadenylation status before induction of gene expression. However, we found 59 and 57 induced transcripts at 10 min post-HFS using DRS and cDNA sequencing, respectively (Figure 1E, left panels). We did not identify any significantly downregulated transcripts at 10 min. 60 min post-HFS showed more prominent changes in gene expression than the 10 min post-HFS: 127 and 188 transcripts were significantly differentially expressed using DRS and cDNA sequencing, respectively (Figure 1E, right panels). The overlap between the two methods is substantial: 60% of the differentially expressed genes (DEGs) identified by DRS at 10 min were confirmed by cDNA sequencing, and at 60 min it was even over 80% (Figure 1E, F, Supplementary Table 1, Supplementary Table 2).

Numerous specific regulatory motifs reside within mRNA sequences, predominantly in the 3′UTRs. These elements are targets for mRNA-contacting ribonucleoprotein molecules or proteins. Among them, CPEB proteins play important regulatory roles in affecting the dynamics of poly(A) tails [33,34]. Therefore, we investigated the presence of a CPEB-binding motif in the DEGs. Indeed, a significant fraction of upregulated transcripts harbor CPEB-binding sites (Figure 1E, F; see also Figure 2A, 3B).

We conclude that LTP-inducing stimulation *in vivo* leads to the expected changes in gene expression as determined by both DRS and cDNA long-read sequencing, providing a basis for a detailed survey of the mRNA 3′-ends and poly(A) tails.

Dynamics of mRNA poly(A) tail lengths following LTP induction

Next, we investigated poly(A) tail dynamics following activity-dependent synaptic plasticity using the DRS and cDNA-seq datasets.

Indeed, we observed changes in the distribution of poly(A) tail lengths, with a gradual increase in a subset of transcripts affected upon LTP (Figure 2A). Initially, 10 min post-HFS, a significant change of tail length occurred in 54 genes, of which 44 underwent tail extension. The Cohen's d effect size of this elongation was medium for ten genes (*Nrn1, Egr3, Sat1, Vgf, Dstnl1, Arpp21, Egr1, Fosl2, Ddit3 and Spns2*; with a mean tail length difference between ipsi-and contralateral hemispheres of 42.3 nt), small for 27 (e.g. *Actb, Nefl, Dnaja1, Nefm, Nptx1, Dclk1I;* with a mean tail length difference between ipsi-and contralateral hemispheres of 20.0 nt), and negligible for 4 genes (*Tuba1a, Ckb, Enc1, Hsp90aa1*; with a mean tail length difference between ipsi-and contralateral hemispheres of 7.59 nt). Among them, the most significantly enriched GO-terms were associated with synapse organization, activity, and transport (Supplementary Figure 2). In contrast, 60 min post-HFS, a significant change in tail length occurred in 417 genes, 74 of which were elongated. The size of this effect was large for 8 genes (*Baiap2, Arpp21, Homer1, Nrbf2, Jarid2, Plekha2, Htra4, Mob3a*; with a mean tail length difference between ipsi-and contralateral hemispheres of 74.38 nt), medium for 22 genes (e.g. *Nrn1, Rheb, Vgf, Rtn4rl2, Egr3, Rbbp7, Synpo* and *Penk*; with a mean tail length difference between ipsi-and contralateral hemispheres of 45.64 nt), small for 40 genes (e.g. *Nefl, Dnaja1, Nefm, Nptx2, Dclk1, Nrp1* and *Stmn4*; with a mean tail length difference between ipsi-and contralateral hemispheres of 21.5 nt) and negligible for 4 genes (*Actb, Rpl41, Nptx1* and *Tubb4b*; with a mean tail length difference between ipsi-and contralateral hemispheres of 8.94 nt). The most enriched GO-terms were linked to cell projection and synapse organization, protein trafficking, and neurodevelopment (Supplementary Figure 2).

We then compared changes in mRNA expression with changes in average tail length to analyze whether they correlate (Figure 2B). At both time points, we observed accumulation of certain mRNAs (e.g., *Nefl, Nrn1, Baiap2, Homer1*), including known IEGs (e.g., *Egf3, Nr4a1*) with elongated poly(A) tails. Simultaneously, a large number of mRNAs with shortened poly(A) tails at the 60 min time point correlated with their downregulation. All this suggests that poly(A) tail extension is driven by transcriptional induction and nuclear 3′-end formation rather than local cytoplasmic processes. Downregulated mRNAs are at the same time undergoing deadenylation-dependent decay manifested by shortened poly(A) tails. Deadenylation is likely to accelerate because *Btg2*, a general deadenylation activator, is among the IEGs induced by the HFS (see Figure 1E) [35]. We also detected a handful of transcripts in which the elongation of poly(A) tail was independent of gene expression upregulation. Those included *Enc1* and *ActB.*

Since mRNAs bound by CPEB proteins are predicted to be the major targets of cytoplasmic poly(A) tail lengthening, we then narrowed our investigation to transcripts containing CPEB motifs (CPEB1 and CPEP2,4) and compared them with the overall changes in poly(A) tail length distribution [36] (Figure 3A, B). In general, the presence of CPEB-binding motifs did not correlate with poly(A) length distribution. Elongation was only observed on DEGs with the strongest effect on mRNAs with CPEB1-binding motif 10 min post-LTP (Figure 3B, Supplementary Figure 2).

Ultimately, we examined specific transcripts recognized for their significant role in hippocampal synaptic plasticity (Figure 3C). Yet again, we did not see signs of cytoplasmic polyadenylation in our data. Notably, this was also the case for *Camk2a* ($Ca2^{+}$/calmodulin-dependent protein kinase 2), acknowledged for its activity-dependent polyadenylation (Figure 3C) [9,37]. This unexpected outcome may be attributed to the relatively lower coverage provided by DRS compared to amplification-based methods. Therefore, we corroborated our findings with our cDNA data. Noteworthy, DRS and cDNA turned out to be fully consistent in estimating tail length distributions (Supplementary Figure 3).

These findings demonstrate that the poly(A) tail length of certain mRNAs increases as a result of polyadenylation of the nascent mRNAs. Furthermore, none of the mRNAs with elongated tails exhibited a significant reduction in accumulation or a detectable decrease in short-tailed read abundance, which corresponds with previous studies [11].

Several mRNAs feature LTP-induced changes in APA site usage

Most mammalian genes contain multiple polyadenylation sites located predominantly within the 3′UTR region of the mRNA (Figure 4A). Because 3′UTRs often contain binding motifs for RNA-binding proteins and miRNA target sites, alterations in their length present an efficient method for regulating gene expression. Alternative polyadenylation (APA) site usage is another post-transcriptional mechanism postulated to be pivotal in LTP [3]. Therefore, we sought to explore whether and how alternative polyadenylation site usage is changed after *in vivo* LTP induction in the rat brain [38,39]. To examine APA profiles following LTP induction, we investigated cDNA reads. Since cDNA sequencing was considerably deeper than DRS, more accurate profiling could be achieved. First, to ensure that the cDNA data was free of nanopore systemic errors (e.g. fused reads), the datasets were curated using pychopper. Subsequently, we applied TAPAS, a software for detecting APA events in sequencing data [40].

With TAPAS, we identified over 19,000 unique polyadenylation sites (PASs) in more than 13,500 genes, of which over 3,500 (~30%) contained at least two PASs, without significant difference in the number of PASs per gene between LTP and control samples (Figure 4B). Motif enrichment analyses of sequences around PASs confirmed the significant overrepresentation of hexamer motif A[U/A]UAAA and its variants approximately 20 nt upstream of PASs (Figure 4C). Results were comparable for both control and LTP samples 10 min and 60 min post-HFS, and they were in agreement with previous studies [3,41].

Most of the identified PASs were already known. Nearly half of these were found in the 3'UTRs, ~10% within transcripts (including introns), and ~3% in exons. Notably, however, more than 30% of detected PASs were identified as intergenic (i.e. located outside 3'UTR in the reference annotation), which is consistent with numerous reports demonstrating that transcripts in the nervous system are equipped with long UTRs [42,43] (Figure 4D). We then corrected and supplemented the predictions from TAPAS with another tool, LAPA [44]. In such a way, we generated a resource of high confidence set of PASs clusters which is a comprehensive annotation of 3′UTRs and PASs in transcripts from the rat brain (Supplementary Resource).

Next, we analyzed 3′UTR APA events and determined whether the length of 3′UTR was changed globally following LTP induction. In the total number of 9228 high-confidence genes, we identified 186 differentially used PASs in 174 genes 10 min after LTP induction and 556 differentially used PASs in 480 genes 60 min post-HFS (Figure 4E). A common set of 115 genes changing expression between time points included immediate early genes, such as *Arc*, *Fos*, *Jun*, *Btg2*, *Bdnf*. According to the GO term analysis, genes with differentially used PASs were enriched in cognition, learning and memory 10 min after HFS, and rhythmic processes, regulation of phosphorus/phosphate metabolic processes and axonogenesis 60 min after LTP induction (Supplementary Figure 4). *Bdnf* is an example of activity-regulated mRNA with multiple APA sites [45]. Here, we show that 10 min post-HFS, the isoform of *Bdnf* mRNA with longer 3′UTR is more abundant, whereas 60 min post-HFS, isoform with short 3'UTR is predominant.

Notably, we observed a strong link between LTP-induced changes in PAS usage and LTP-induced changes in transcript abundance (Figure 4E, compare to Figure 1E). Furthermore, among all reported APA events, we noticed a general tendency to shorten the 3′UTRs, regardless of time point (Figure 3F). This suggests that proximal PASs might be favored

when expression increases, possibly due to their higher efficiency over distal sites or to avoid expression inhibition mediated by miRNAs [3,41].

Neuronal mRNAs with semi-templated poly(A) tails rich in non-adenosine residues

We then examined the nucleotide composition of poly(A) tails in DRS reads using our recently developed software, Ninetails [23]. Remarkably, in data from both hemispheres (10 and 60 min post-HFS and in corresponding controls), we observed a fraction of tails containing non-adenosines (Figure 5A), mostly found only one instance of non-adenosine per tail, rarely two or more, coherent with our recent data (Figure 5B) [19,23]. The global proportion of decorated tails was relatively low, slightly above 3%, remaining stable across the conditions (Figure 5A). Subsequently, we focused on certain groups of reads: mitochondrial, DEGs 10 min post-HFS, DEGs 60 min post-HFS and potential CPEB targets. In our recent study, we found that mitochondrial transcripts have short but highly decorated tails, reflecting various fidelities of the cellular poly(A) polymerases [23,46]. Here, in data from both hemispheres, the proportion of decorated tails in mitochondrial transcripts was also relatively high and nearly equivalent to the total. It also remained relatively constant, as the distribution of their tail lengths (Figure 5A). Conversely, in both DEGs subsets and in transcripts containing CPE motifs, we observed an elevated proportion of decorated reads following LTP induction compared to the corresponding controls (Figure 5A). This can be attributed to the activation of transcriptional mechanisms leading to the synthesis of new molecules with longer tails, wherein polymerase-induced errors are more likely [23].

We also noticed that non-adenosines are more common in longer tails (Supplementary Figure 5A), suggesting that they are inserted late by terminal nucleotidyltransferases (TENTs) in the cytoplasm [46–48]. The obvious candidates are TENT4A/B known for their incorporation of non-adenosines (Supplementary Figure 5B) [46–49], which is supported by the fact that at the global level guanosine is most prevalent, followed by cytidine and uridine (Figure 5C, D), This contrasts with other experimental systems, where cytidine is the most common and guanosine the least common [19,23]. Notably, gene level analysis followed by closer inspection of Ninetails output and raw nanopore signals unveiled a subset of transcripts with tails significantly enriched in non-adenosines. The most notable example is the *Nrgn* gene, where nearly 60% of the tails were decorated with (often multiple) guanosines (Figure 5D, E, F). According to APA analysis results, *Nrgn* has two PASs (Supplementary Resource, Supplementary table 3). Reads utilizing the distal PAS have blank tails (i.e. containing exclusively adenosines), whereas reads using the proximal PAS have highly decorated tails with a strikingly repetitive non-adenosine distribution pattern (Figure 5E, F). Further analysis revealed that this

regularity is due to the semi-templated poly(A) tail in the isoform with the shorter 3′UTR, which has an extremely A rich 3′-end (Figure 5E, F). In total, we identified 54 genes (e.g., *Grin2b*, *Kalrn*, and *Shank1*) whose transcripts may possess such semi-templated tails (Supplementary Table 4), which is the source of high guanosine prevalence rather than TENT4A/B activity. Interestingly, the most enriched GO-terms assigned to them were associated with learning, neuron reorganization, memory, and regulation of LTP (Supplementary Figure 5C), suggesting the potential regulatory role of such a newly described group of transcripts.

In the synaptic compartment, the polyadenylation is not induced by NMDA-R stimulation *in vitro*

Potential cytoplasmic polyadenylation in our hippocampal data might have been obscured by highly expressed transcripts from non-neuronal cells or by the predominant effect of transcriptional induction (i.e., the influx of newly synthesized long-tailed molecules)[11]. Unable to indicate transcripts undergoing local polyadenylation in the whole dentate gyrus in response to HFS, we chose a more specific setup: synaptoneurosomes stimulated chemically *in vitro* (Figure 6A) (for details see Methods) [50,51]. Enrichment and stimulation of synaptoneurosomes were performed using our optimized protocol [50,51]. The effectiveness of this protocol can be confirmed by western-blots (e.g. depletion/enrichment of specific markers and phosphorylation of ERK kinases) (Supplementary Figure 6A, B).

We performed DRS of mRNAs isolated from NMDA-R-stimulated synaptoneurosomes and corresponding controls to gain an accurate view of extranuclear polyadenylation (4 replicates). As expected, we did not observe differences in transcript abundance between the conditions (Supplementary table 5). However, the polyadenylation profile also was largely unchanged (Figure 6B). Specifically, no shift of putative dormant transcripts towards longer tails was noted in stimulated synaptoneurosomes [8,11]. Instead, we observed a very small fraction of oligoadenylated mRNAs and general slight shortening poly(A) tail lengths compared to controls. Analyzing poly(A) tail length distribution in transcripts related to synaptic plasticity also failed to confirm local cytoplasmic polyadenylation upon stimulation (Figure 6C). There were also fewer non-adenosines in stimulated synaptoneurosomes than in corresponding controls (Supplementary Figure 6C-E).

Finally, when the poly(A) tail distribution of the synaptoneurosomes and total RNA of dante gyri was compared, the former ones exhibited considerably shorter poly(A) tails (Figure 6D).

In conclusion, synaptic mRNA translation regulation appears uncoupled from polyadenylation.

Discussion

Local protein synthesis at synapses is regulated by several post-transcriptional mechanisms, which is necessary given the distance of synapses from the nucleus-containing cell body. Because of this spatial separation, rapid, on-demand protein synthesis relies on translational rather than transcriptional mRNA regulation. This is evident even in simple *in vitro* systems, where isolated synaptic fractions, when chemically induced, show substantial global activation of protein synthesis [50,51]. Such observations emphasize the role of translation over transcription in these situations.

In our study, we complemented *in vivo* long-term potentiation (LTP) in the rat hippocampus with *in vitro* synaptoneurosomes and applied long-read sequencing technologies: direct RNA and cDNA sequencing. This allowed us to make an unbiased assessment of poly(A) tail dynamics and mRNA 3′-ends, providing valuable resources on APA site usage, tail length distribution, and its nucleotide composition after neuronal stimulation.

It has been postulated that cytoplasmic polyadenylation plays a central role in regulation of translation at synapses [36]. This mechanism, originally observed in developing oocytes and early embryos [52], involves dormant mRNAs with short poly(A) tails that are elongated upon activation by cytoplasmic poly(A) polymerases, rapidly initiating protein synthesis. RNA-binding proteins, in particular the CPEB family, are thought to be key regulators of this polyadenylation process. Interestingly, recent studies suggest that not only the length but also the composition of poly(A) tails influences gene regulation [47]. Surprisingly, our results did not indicate robust cytoplasmic polyadenylation in the hippocampus, challenging the previously understood role of this mechanism in neuronal function. This raises the question of the physiological role of the relatively abundant GLD2/TENT2 poly(A) polymerase, which was previously hypothesized to be responsible for CPEB-regulated cytoplasmic polyadenylation [53,54]. At the same time, members of another family of cytoplasmic poly(A) polymerases, TENT5, have very low expression in the hippocampus. The remaining two polymerases, TENT4A and TENT4B (GLD4), are known to incorporate guanosines into poly(A) tails [46], and this nucleotide is most abundant in hippocampal mRNAs compared to cyidines and uridines. However, the guanosines are present in less than 4% of the poly(A) tails of hippocampal mRNAs, with the exception of mRNAs described by our group as having semi-templated tails, arguing against a primary role of TENT4A/B is poly(A) tail composition.

Overall, our data suggest that the dynamics of poly(A) tail length that we observed in hippocampal neurons fallowing LTP is mainly related to the transcriptional induction, suggesting that it is mediated by canonical machinery involved in the 3′-end formation. At the same time, we generally observed slightly shorter poly(A) tails in synaptoneurosomes compared to mRNAs from the entire dentate gyrus. This is to be expected since synaptoneurosomes do not contain nascent transcripts that are still present in the nucleus and have the longest tails. Although synaptoneurosomal mRNAs had shorter tails, there was a very small fraction of oligoadenylated mRNAs, which could be re-adenylated in order to drive translation upon stimulation, as proposed for *Camk2a* mRNA. In fact, chemical induction led to the opposite effect: a slight but detectable global poly(A) shortening. As there is growing evidence that deadenylation is a co-translational event, the global activation of translation associated with the deadenylation process explains our observation very well [55]. This is also confirmed by the fact that a large number of mRNAs with truncated poly(A) tails are present in the dentate gyrus 60 min post-HFS. In conclusion, our data do not support cytoplasmic polyadenylation as a mechanism driving translation in hippocampal neurons upon stimulation.

The sequencing data collected allowed us to analyze the alternative polyadenylation site usage, as most mammalian genes possess multiple polyadenylation sites that generate mRNAs with alternative 3′-ends [5]. Previous research has demonstrated that *in vitro* LTP, when induced in brain slices, results in widespread shortening of 3′UTRs, consistent with our observation of the general trend of 3'UTR shortening following *in vivo* induced LTP in the rat hippocampus [3]. This indicates a preference for proximal PASs during periods of increased expression, likely due to their greater efficiency compared to distal sites or to circumvent expression suppression by miRNAs [3,41].

Finally, studies of the nucleotide composition of poly(A) tails have led us to the discovery of a group of transcripts with semi-templated poly(A) tails. Some of these mRNAs encode proteins that play an important roles in synaptic physiology, such as neurogranin [56]. Since non-adenosine residues inhibit deadenylation, such transcripts may be particularly stable, adding another layer of complexity [57]. These findings call for further functional analyses to decipher the full spectrum of poly(A) tail-mediated regulation in neuronal physiology. Various stimulation-induced mechanisms leading to changes in mRNA tail length and abundance further illustrate the dynamic nature of mRNA regulation post-HFS.

Figure legends

Figure 1. *In vivo* hippocampal LTP induction.

(A) Schematic depiction of dentate gyrus with LTP-induction (left hemisphere, ipsilateral) marked in red and control dentate gyrus (right hemisphere, contralateral) marked in blue. (B) Schematic coronal section of the hippocampus with stimulating and recording electrodes positions; DG – dentate gyrus, MF – mossy fibers, SC – Schaffer collateral, PP – perforant path, EC – entorhinal cortex. (C) Representative recordings of HFS-induced LTP in anesthetized rats. Time course plots of percent change in fEPSP slope post-HFS (10 min and 60 min after HFS) relative to baseline. Values are mean ± SEM. Red arrows represent three sessions of HFS. insert: Representative traces before (baseline, green) and after HFS (post-HFS, red. (D) Expression levels of selected IEGs induced in the dentate gyrus following LTP induction (Ipsi) as compared to control (Contra). Colors indicate normalized expression values as shown by the scale on the left (log2 change). (E) DEGs in the rat dentate gyrus after *in vivo* LTP induction. The expression changes ($\log_2$ ratios) 10 min (left panels) and 60 min (right panels) after HFS. DEGs are colored in red. Genes containing CPEB-binding motifs are marked as crosshair (+), genes lacking CPEB-binding motifs are marked as dots. Results obtained with two Nanopore methods: Direct RNA sequencing (DRS) (top panels) and cDNA sequencing (bottom panels) are shown. (F) The overlap between differentially expressed genes 10 min and 60 min after LTP induction using both DRS and cDNA methods.

Figure 2. Dynamics of mRNA poly(A) tail lengths following LTP induction.

(A) Poly(A) tail length changes 10 min and 60 min after HFS. (B) Differential expression vs differential polyadenylation for 10 min post-HFS and 60 min post-HFS. Genes with significantly changed expression and poly(A) length are highlighted (teal). (C) Differential expression vs differential polyadenylation for 10 min post-HFS and 60 min post-HFS. Genes with unchanged expression and significantly changed poly(A) length are highlighted (fuchsia). (D) Distribution of poly(A) lengths in selected transcripts across experimental conditions.

Figure 3. Distribution of poly(A) lengths in selected groups of mRNAs.

(A) Global distribution of poly(A) lengths: upper panel – complete datasets, bottom panel – global distribution without mitochondrially-encoded genes. (B) Distribution of poly(A) lengths in CPEB-targets. Upper left: transcripts with CPEB1-binding motifs (total). Upper right: transcripts with CPEB2,4-binding motifs (total). Middle left: transcripts with CPEB1-binding motifs which were differentially expressed 10 min after LTP induction. Middle right:

transcripts with CPEB1-binding motifs which were differentially expressed 60 min after LTP induction. Bottom left: transcripts with CPEB2,4-binding motifs which were differentially expressed 10 min after stimulation. Upper right: transcripts with CPEB2,4-binding motifs which were differentially expressed 60 min after LTP induction. In each panel, all conditions were included.

Figure 4. Differential polyadenylation site usage.

(A) Schematic depiction of 3′UTR containing multiple PASs. (B) Number of PASs per gene reported by TAPAS. (C) Enriched motifs near detected PASs. (D) Genomic location assignment of reported PASs. (E) Relationship between PASs usage and expression level. (F) Usage of distal and proximal PASs in genes with at least two PASs reported. (G) An example of a gene associated with neuroplasticity (*Bdnf*) exploiting multiple PASs with differential frequency. A genome browser-like view of coverages in 3′UTR region across conditions is shown.

Figure 5. Non-adenosine residues in poly(A) tails; Neurogranin as an example of semi-templated poly(A) tails with increased frequency of non-adenosine residues.

(A) Frequency of reads with poly(A) tails decorated with non-adenosines. Data normalized on y-axis (each group separately). (B) Frequencies of decorated reads with a given number of non-adenosines. (C) Frequency of non-adenosine residues (cytidine, guanosine, and uridine, respectively) in selected groups of reads: total datasets, mitochondrially-encoded genes, DEGs (each time point separately) and in CPEB targets (aggregated). (D) Example nanopore signals corresponding to decorated tails. Non-adenosine residues reported by Ninetails are shown. (E) Genome-browser plot of reads aligned to 3'UTR of *Nrgn* gene with an example of corresponding nanopore signal revealing semi-templated poly(A) tail origin in isoform using proximal PAS and internal non-adenosines (guanosines) in fixed positions. (F) Example nanopore signals corresponding to semi-templated tails of Nrgn isoform with shorter 3′UTR. Non-adenosine residues (guanosines) in fixed positions reported by Ninetails are shown.

Figure 6. Poly(A) tail length distribution in synaptoneurosomes 10 min after *in vitro* NMDA-R stimulation.

(A) Schematic depiction of synaptoneurosomes isolation and *in vitro* stimulation. (B) Polyadenylation profile of mRNAs in synaptoneurosomes upon NMDA-R stimulation. (C) Poly(A) tail length distribution in selected groups of transcripts in synaptoneurosomes. Upper left: global (total datasets). Upper right, bottom left, and bottom right, respectively: *Camk2a*, *Baiap2*, and *Nefl* – genes related to synaptic plasticity. (D) Poly(A) tail length distribution in

selected groups of transcripts in synaptoneurosomes vs dentate gyrus. The data from the given hemisphere in dentate gyrus were aggregated across time points for clarity.

Supplemental information titles and legends

Supplementary Figure 1. Reverse transcription-quantitative PCR (RT-qPCR) analysis of *Arc* and *Fos* expression.

Supplementary Figure 2. Top 15 GO-terms of selected groups of transcripts ordered by gene ratio. GO-terms in dentate gyri shown for (A) upregulated DEGs (B) transcripts with significantly elongated poly(A) tails (C) upregulated transcripts with CPE motifs.

Supplementary Figure 3. Two Oxford Nanopore sequencing methods used in this study. A comparison of poly(A) tail lengths distribution in selected transcripts reveals high concordance between Oxford Nanopore DRS and cDNA sequencing protocols.

Supplementary Figure 4. Top 15 GO-terms of genes with differential PASs usage ordered by gene ratio.

Supplementary Figure 5. Profiling of non-adenosine composition in hippocampus upon LTP induction. (A) Dynamics of non-adenosine residues in *Camk2a.* First row: frequency of read categories. Second row: frequency of tails with given non-adenosines. Third row: poly(A) tail length distribution of reads from either category. Fourth row: estimated positions of non-adenosines within poly(A) tails. (B) Expression of TENTs and deadenylases in dentate gyrus. (C) Enriched GO-terms in transcripts decorated with semi-templated poly(A) tails from dentate gyri (both time points aggregated).

Supplementary figure 6. Confirmation of synaptosome enrichment and nucleotide composition of synaptosomal poly(A) tails. (A) Western blot validation of synaptoneurosome fractionation revealing the enrichment of both pre- and postsynaptic markers, but not glia (Gfap) and nuclear (Kdm1 and c-Jun) markers in the synaptoneurosomal fraction. **(B)** Western blot on synaptoneurosomes confirming activation of extracellular signal-regulated protein kinases 1 and 2 (ERK1/2) in response to the stimulation (0-10 min). (C-E) Analysis of nucleotide composition of poly(A) tails in synaptoneurosomal data with the Ninetails. **(C)** Frequency of reads decorated with non-adenosines, **(D)** reads decorated with given amount of non-adenosines, and **(E)** given non-adenosines (cytidine, guanosine, and uridine, respectively).

Supplementary Table 1. Summary of dentate gyri DRS data per gene. (A) Differential expression and differential adenylation data for 10 min timepoint. **(B)** Differential expression and differential adenylation data for 60 min timepoint. **(C)** GO-terms for genes with significantly elongated poly(A) tails in 10 min timepoint. **(D)** GO-terms for genes with significantly elongated poly(A) tails in 60 min timepoint. **(E)** GO-terms for upregulated genes in 10 min timepoint. **(F)** GO-terms for upregulated genes in 60 min timepoint. **(G)** GO-terms for upregulated genes with CPEB-binding motifs in 10 min timepoint. **(H)** GO-terms for upregulated genes with CPEB-binding motifs in 60 min timepoint.

Supplementary Table 2. Summary of dentate gyri cDNA data per gene. (A) Differential expression and differential adenylation data for 10 min timepoint. **(B)** Differential expression and differential adenylation data for 60 min timepoint. **(C)** GO-terms for genes with significantly elongated poly(A) tails in 10 min timepoint. **(D)** GO-terms for genes with significantly elongated poly(A) tails in 60 min timepoint. **(E)** GO-terms for upregulated genes in 10 min timepoint. **(F)** GO-terms for upregulated genes in 60 min timepoint. **(G)** GO-terms for upregulated genes with CPEB-binding motifs in 10 min timepoint. **(H)** GO-terms for upregulated genes with CPEB-binding motifs in 60 min timepoint.

Supplementary Table 3. High-confidence PASs. (A) PASs predicted for datasets obtained 10 min after LTP induction by TAPAS. **(B)** High confidence poly(A) clusters predicted by LAPA for datasets obtained 10 min after LTP induction. **(C)** PASs predicted for datasets obtained 60 min after LTP induction. **(D)** High confidence poly(A) clusters predicted by LAPA for datasets obtained 60 min after LTP induction.

Supplementary Table 4. Nonadenosine profiling upon LTP induction. (A) Summary of Ninetails pipeline for dentate gyrus. **(B)** List of genes containing semi-templated poly(A) tails with their 3′UTR coordinates.

Supplementary Table 5. Summary of synaptoneurosomal DRS data per gene. Differential expression and differential adenylation data.

Supplementary Table 6. Characteristics of analyzed material. Detailed information with sequencing depth, accession numbers, software used for analyses, and additional data characteristics.

Supplementary Resource High-confidence poly(A) clusters annotation in bed format.

STAR Methods

Key resources table

REAGENT or RESOURCE	SOURCE	IDENTIFIER
Antibodies		
c-Jun	Cell Signaling	Cat#9165
Gfap	Proteintech	Cat#16825-1-AP
GluA2	Cell Signaling	Cat#13607
Hsp90	Abcam	Cat#ab13495
Kdm1	Abcam	Cat#ab129195
Psd95	Merck Millipore	Cat#MAB1598
synaptophysin	Merck Millipore	Cat#MAB329
tubulin	Santa Cruz Biotechnology	Cat#sc-134239
Chemicals, peptides, and recombinant proteins		
Agilent RNA 6000 Nano Kit	Agilent	Cat#5067-1511
cOmplete™, EDTA-free Protease Inhibitor Cocktail	Roche	Cat#05056489001
GlycoBlue™ Coprecipitant	Invitrogen	Cat#AM9515
KAPA Pure Beads	Roche	Cat#07983298001
N-Methyl-D-aspartic acid (NMDA)	Sigma-Aldrich	Cat#M3262
PowerUp SYBR Green Master Mix	Thermo Fisher Scientific	Cat#A25742
RiboLock RNase Inhibitor	Thermo Fisher Scientific	Cat#EO0381
Critical commercial assays		
TGX Stain-Free FastCast Acrylamide Kit, 10%	BioRad	Cat#161-0183
Amersham ECL Prime Western Blotting Detection Reagent	GE Healthcare	Cat#RPN2236
Phospho-MAPK Family Antibody Sampler Kit	Cell Signaling	Cat#9910
MAPK Family Antibody Sampler Kit	Cell Signaling	Cat#9926
Direct RNA Sequencing Kit	Oxford Nanopore Technologies	SQK-RNA002
cDNA-PCR Sequencing Kit	Oxford Nanopore Technologies	SQK-PCS111
Deposited data		
Nanopore sequencing data	this paper	PRJEB75352
Nanopore sequencing data	Czarnocka-Cieciura et al. 2023 [58]	PRJEB75356
Supplementary non-sequencng data	this paper	Zenodo (currently embargoed; reviewer token provided)
Experimental models: Organisms/strains		
Rat: Sprague Dawley	IMDiK, Warsaw	Tac:Cmd:SD
Oligonucleotides		
random primers	GeneON	Cat#S300

cFos Fwd: 5’CCCATCCTTACGGACTCCC3’	this paper	N/A
cFos Rev: 5’GAGATAGCTGCTCTACTTTGCC3’	this paper	N/A
Arc Fwd: 5’AAGTGCCGAGCTGAGATGC3’	this paper	N/A
Arc Rev: 5’CGACCTGTGCAACCCTTTC3’	this paper	N/A
18S rRNA Fwd: 5’GTTGGTTTTCGGAACTGAGGC3’	this paper	N/A
18S rRNA Rev: 5’GTCGGCATCGTTTATGGTCG3’	this paper	N/A
Software and algorithms		
clusterProfiler 4.0	Wu et al. 2021 [59]	https://guangchuangyu.github.io/software/clusterProfiler/
ComplexHeatmap 7d95ca5	Gu 2022 [60]	https://github.com/jokergoo/ComplexHeatmap
DESeq2 1.34.0	Love et al. 2014 [61]	https://bioconductor.org/packages/release/bioc/html/DESeq2.html
Dorado 0.5.3	Oxford Nanopore Technologies	https://community.nanoporetech.com/posts/dorado-0-5-3-release
ggplot2 3.4.1	Wickham 2016 [62]	https://github.com/tidyverse/ggplot2/releases
g:Profiler2 0.2.1	Raudvere et al. 2019 [63]	https://cran.r-project.org/web/packages/gprofiler2/index.html
GraphPad Prism 7.0	GraphPad	https://www.graphpad.com/scientific-software/prism/
Guppy 6.0.0	Oxford Nanopore Technologies	https://community.nanoporetech.com/posts/guppy-v6-0-0-release
LAPA eb16fee	Çelik et al. 2022 [44]	https://github.com/mortazavilab/lapa
MEME 5.4.1	Grant et al. 2011 [64]	https://meme-suite.org/meme/doc/download.html
minimap2 2.17	Li 2018 [65]	https://github.com/lh3/minimap2
nanopolish 0.13.2	Workman et al. 2019 [22]	https://github.com/jts/nanopolish
NanoTail 0.1.0	Krawczyk et al. 2024 [66]	https://github.com/smaegol/nanotail
ninetails 1.0.2	Gumińska et al. 2024 [23]	https://github.com/LRB-IIMCB/ninetails
pychopper 2.7.2	Oxford Nanopore Technologies	https://github.com/epi2me-labs/pychopper
python 3.8.15	Python Software Foundation	https://www.python.org/downloads/release/python-3815/
R 4.1.2	R Core Team	https://cran.r-project.org/src/base/R-4/R-4.1.2.tar.gz
samtools 1.9	Danecek et al. 2021 [67]	https://github.com/samtools/samtools/releases

subread 2.0.6	Liao et al. 2014 [68]	https://github.com/ShiLab-Bioinformatics/subread
TAPAS d231ad5	Arefeen et al. 2018 [40]	https://github.com/arefeen/TAPAS
Other		
Nylon Net Filters; 100 µm, 60 µm, 30 µm, 10 µm	Merck Millipore	Cat#NY1H02500, Cat#NY6002500, Cat#NY3002500, Cat#NY1002500

Resource availability

Lead contact

Further information and requests for resources and reagents should be directed to and will be fulfilled by the lead contact, Andrzej Dziembowski (adziembowski@iimcb.gov.pl).

Materials availability

The materials used in this study are available without restriction.

Data and code availability

The raw sequencing data (fast5 files) were deposited at the European Nucleotide Archive (ENA) (https://www.ebi.ac.uk/ena/browser/home) under the project numbers (PRJEB75352 and PRJEB75356) with sample numbers listed in Supplementary Table 6 and will be released upon publication.

Source data used for plotting are provided in Supplementary tables 1-5. Supplementary Tables are also available on Zenodo under doi: 10.5281/zenodo.11478468 and will be released upon publication.

The custom software (NanoTail) used for poly(A) tail analysis in R is available here: (https://github.com/LRB-IIMCB/nanotail). The custom software (Ninetails) used for non-adenosine profiling is available here (https://github.com/LRB-IIMCB/ninetails).

All additional custom code is available from the authors upon request.

Experimental model and subject details

Animals

Young adult male Sprague Dawley rats were used (5 months old, 200-300g). They were kept in the laboratory animal facility under a 12-h light/dark cycle with food and water available *ad libitum*. These experimental procedures were approved by Norwegian National Research Ethics Committee in compliance with EU Directive 2010/63/EU, ARRIVE guidelines. Experiments were conducted by the Federation of Laboratory and Animal Science Associations (FELASA) C course-trained and certified researchers.

Method details

Stereotaxic surgery and electrode positioning

Rats were anesthetized with 1.5mg/kg of urethane injected intraperitoneally. Once they were unreactive to toe pinch, animals were placed in a stereotaxic frame (David Kopfs Instruments, USA) to fix the head. A thermostatically controlled heating pad was placed under the animal to maintain a temperature of 37°C. The scalp was then cut longitudinally, and the skin held back from the scalp using bulldog clamps. Two burr holes were drilled rostral to bregma to attach the ground and reference screws. For the stimulating electrode, a craniotomy was made on the left hemisphere using bregma as a point of reference (7.9 mm caudal, 4.2 mm lateral, 2.5 mm ventral), these coordinates pinpoint the angular bundle of the medial perforant path. For the recording electrode, a craniotomy was made on the left hemisphere using bregma as a point of reference (3.9 mm caudal, 2.3 mm lateral, ~2.5-3 mm ventral), these coordinates pinpoint the hilar region of the dentate gyrus. The exact depth of the recording electrode was determined when test pulses triggered the maximum fEPSP slope (see next paragraph).

In-vivo electrophysiology

The stimulating electrode sent test pulses every 30 s unilaterally into the medial perforant path in order to evoke field potentials (fEPSPs) in the hilar region of the dentate gyrus which were measured extracellularly using a recording electrode. Stimulus intensities, typically between 100-500 microamps, were set such that they evoked 1/3 of maximum population spike. Baseline potentials were recorded for 24 min. When baseline recordings were completed, the current intensity was doubled and HFS was applied to induce long-term potentiation (LTP). The simulator used was a Grass S88 Dual output stimulator (Grass Medical Instruments, model S88D). The HFS paradigm consisted of three sessions with 5-min intervals totaling 10 min and 30 s. Each session had four trains of 8 pulses delivered at 400 Hz with 10 second intervals between each train. In total there were 96 pulses as previously described [69]. Post-HFS application, the current was immediately reduced to its test pulse value and the recordings continued at 0.033 Hz for either 10 min or 60 min depending on the experimental group.

Field excitatory postsynaptic potentials (fEPSPs) were recorded using Data Wave Technologies Work Bench Software (Longmont, CO). fEPSP slope was calculated using the maximum positive dV/dt in a selected time window between the fEPSP onset to one-third of the positive peak, based on test-pulse responses during baseline recording. This was done in order to scrutinize only the early EPSPs characteristic of the monosynaptic connection from the entorhinal cortex to the dentate gyrus. Data on the slope and population spike amplitude

were transferred to Microsoft Office Excel 2010 (Microsoft Corporation, USA). Every 4 measurements were transformed into a 2-min mean and normalized to the mean of the 24 min of baseline recording. This is to reduce variability and investigate percent change from the average baseline value (average of 4 data points every 30 s so one datapoint is obtained for every 2 min of data). Slope and population spike amplitude averages were analyzed in GraphPad Prism (San Diego, CA), comparing baseline to post-HFS.

Brain dissection

Immediately after the experiment, the rat was removed from the stereotax. For dissection: the brain was removed from the skull and placed on filter paper above a glass plate cooled with ice. Ice-cold saline solution was used periodically through the dissection to cool the brain down. With the hippocampus isolated, blood vessels and connective tissue were removed before the Cornu Ammonis regions were separated from the dentate gyrus and each was put in cold microtubes. The samples were put on dry ice and kept at −80°C. This was done for both the ipsilateral and contralateral dentate gyri.

RNA Extraction and Quality Check

Prior to homogenization tissue was carried on dry ice and then homogenized in 1 mL of Trizol using 1 mL glass/glass dounce homogenizer. Homogenate was transferred to 1.5 ml LoBind® type Eppendorf tube and centrifuged 12000 x g for 5 min in 4°C, due to its high fat content. RNA was then extracted from supernatant using standard manufacturer's protocol. Precipitation was carried out by addition of glycogen (GlycoBlue™ Coprecipitant (15 mg/mL)) (30 µg per sample), 1 volume of isopropanol and overnight incubation in -20°C. RNA pellet was dissolved in RNAse free dd H_2O and preliminary assessed in terms of quality using Nanodrop 2000 Spectrophotometer yielding on average around 20µg of RNA per sample. RNA was then subjected to further purification by precipitation with 3 volumes of KAPA Pure Beads according to manufacturer’s instructions (KAPA Biosystems). The assessment of RNA integrity number (RIN) was carried out using the Agilent bioanalyzer platform (Agilent RNA 6000 Nano Kit). RNA from synaptoneurosomes was isolated using the same method. The amount of Trizol used was approximately 1 mL per 100 mg of synaptoneurosomes pellet.

qRT-PCR

1 µg of RNA samples were reverse transcribed using random primers (GeneON, Ludwigshafen am Rhein, Germany; #S300; 200 ng/RT reaction) and SuperScript IV Reverse Transcriptase (Thermo Fisher Scientific). Next, the cDNA samples were amplified using

specific primers (listed in Key resource table). Each reaction was setin a final volume of 15 µl, using PowerUp SYBR Green Master Mix (#A25742 Thermo Fisher Scientific) in a LightCycler480 (Roche). Fold changes in expression were determined using the ΔΔ Ct (where Ct is the threshold cycle) relative quantification method. Values were normalized to the relative amounts of 18S rRNA.

Nanopore direct RNA sequencing

The DRS was performed following Bilska et al. [70]. For dentate gyri, 4.5-5 µg of total RNA was mixed with 250 ng of oligo(dT)-enriched RNA from *Saccharomyces cerevisiae* and 5 ng of *in vitro* transcribed poly(A) standards. For synaptoneurosomes, 3 µg of cap-enriched RNA was mixed with 200 ng of *S. cerevisiae* oligo(dT)-enriched RNA and 5 ng of poly(A) standards. Libraries were prepared using the Direct RNA Sequencing Kit SQK-RNA002 (ONT). Sequencing utilized FLO-MIN106 R9.4.1 RevD flow cells on a MinION device controlled by MinKNOW software (ONT). Basecalling was performed with Guppy 6.0.0 (ONT).

Nanopore cDNA sequencing

For dentate gyri, 200 ng of total RNA was used to prepare nanopore cDNA sequencing libraries with the cDNA-PCR Sequencing Kit SQK-PCS111 (ONT) according to the manufacturer's instructions. Sequencing was carried out using FLO-MIN106 R9.4.1 RevD flow cells on a MinION device controlled by MinKNOW software (ONT). The basecalling was performed with Guppy 6.0.0 (ONT) and Dorado 0.5.3 (ONT).

Poly(A) tail length profiling

Basecalled RNA reads were mapped to mRatBN7.2-derived reference transcriptome using minimap2 2.17 (Li, 2018) (-k 14 -ax map-ont --secondary = no) and processed using samtools 1.13 [67] to filter out supplementary alignments and reads mapping to the reverse strand (samtools view -b -F 2320). The lengths of the poly(A) tails were estimated using the Nanopolish 0.13.2 polya function [22]. Only reads tagged by Nanopolish as PASS or SUFFCLIP were considered in the following analyses.

The lengths of poly(A) tails in cDNA reads were estimated during basecalling with dorado (--estimate-poly-a), extracted from the source files, and aggregated in tabular form.

Differential expression

Reads were mapped to the mRatBN7.2 reference genome using minimap2 2.17 [65] (-ax splice --secondary = no -uf). The read distribution across genes was summarized using featureCounts

from the Subread 2.0.6 package [68] (-L --fracOverlap 0.5 --fracOverlapFeature 0.5 -s 1). Reads overlapping multiple features and multimappers were excluded. Differential expression analysis was performed using the DESeq2 [61] with default settings.

Nucleotide composition of poly(A) tails

Non-adenosine nucleotides in DRS reads were assessed with the Ninetails package [23]. The raw classification results were corrected and further processed as described in Gumińska et al. [23].

Alternative polyadenylation

The cDNA reads were preprocessed using pychopper 2.7.2 (ONT). Reads fulfilling quality criteria and rescued fused reads were combined, then mapped to the mRatBN7.2 reference genome with minimap2 2.17 [65] (-ax splice --secondary = no -uf -k 14). Alternative polyadenylation site analysis was performed with TAPAS [40] and LAPA [44].

CPEB-binding motif search

CPEB-binding motifs (CPEB-1 and CPEB2-4, respectively) were searched for using the FIMO software (--bgfile --nrdb-- --thresh 1.0E-4) from the MEME suite [64]. Gene ontology enrichment was performed using g:Profiler [63] and ClusterProfiler [59].

Synaptoneurosomes isolation and in vitro stimulation

Synaptoneurosomes were prepared as described previously [51]. Before tissue dissection, Krebs buffer (2.5 mM $CaCl_2$, 1.18 mM KH_2PO_4, 118.5 mM NaCl, 24.9 mM $NaHCO_3$, 1.18 mM $MgSO_4$, 3.8 mM $MgCl_2$, and 212.7 mM glucose) was aerated with an aquarium pump for 30 min at 4°C. Next, the pH was lowered to 7.4 using dry ice. The buffer was supplemented with 1× protease inhibitor cocktail complete EDTA-free (Roche) and 60 U/ml RNase Inhibitor (RiboLock, Thermo Fisher Scientific). Animals were euthanized by cervical dislocation; hippocampi were dissected. Tissue from one hemisphere was homogenized in a 1.5 ml Krebs buffer using Dounce homogenizer with 10–12 strokes. All steps were kept ice-cold to prevent the stimulation of synaptoneurosomes. Homogenates were passed gravitationally through a series of presoaked (with Krebs buffer) nylon mesh filters: 100, 60, 30, and 10 µm (Merck Millipore) in cold room to 50-ml polypropylene tube, centrifuged at 1,000 g for 15 min at 4°C, and washed, and pellet was resuspended in Krebs buffer with protease and RNase inhibitors. The protocol for *in vitro* stimulation of NMDA receptors on synaptoneurosomes was described before (Kuzniewska et al 2018). The aliquots of freshly isolated synaptoneurosomes were prewarmed for 5 min at 37°C and stimulated with a pulse of 50 µM

NMDA and 10 μM glutamate for 30 s; then, APV (120 μM) was added and synaptoneurosomes were further incubated for 10 min at 37°C. Unstimulated samples, kept on ice, were used as controls. Synaptoneurosomes isolated from 5 rats were pooled together and split into two samples (control and NMDAR-stimulated) in order to obtain enough material for Nanopore Direct RNA Sequencing (DRS). Four independent synaptoneurosomes isolations were used for DRS.

Western blotting analysis of synaptoneurosomal preparations

Equal amounts of protein from homogenate and synaptoneurosomal fraction were resolved on SDS-PAGE (10%, TGX Stain-Free FastCast Acrylamide Solutions, BioRad). After electrophoresis proteins in the gel were visualized using Bio-Rad's ImageLab software to verify the equal protein loading. Proteins were transferred to PVDF membranes (pore size 0.45 μm, Immobilon-P, Merck Millipore) using Trans-Blot Turbo Blotting System (BioRad; 170-4155). Membranes were blocked for 1 h at room temperature in 5% non-fat dry milk in PBS-T (PBS with 0.01% Tween-20), followed by overnight incubation at 4°C with primary antibodies (synaptophysin Cat#MAB329, Merck Millipore; GluA2 Cat#13607, Cell Signaling; Psd95 Cat#MAB1598, Merck Millipore; Gfap Cat#16825-1-AP; Proteintech; tubulin Cat#sc-134239, Santa Cruz Biotechnology; Hsp90 Cat#ab13495, Abcam; Kdm1 Cat#ab129195, Abcam; c-Jun Cat#9165, Cell Signaling) in 5% milk in PBS-T. Blots were washed 3 × 5 min with PBS-T, incubated 1 h at room temperature with HRP-conjugated secondary antibody (1:10 000 in 5% milk) and washed 3 × 5 min with PBS-T. In the case of MAPK/Phospho-MAPK Family Antibody Sampler Kit, membranes were blocked for 1 h at room temperature in 5% bovine serum albumin (BSA) in PBS-T, primary and secondary antibodies were diluted also in 5% BSA in PBS-T. HRP signal was detected using Amersham ECL Prime Western Blotting Detection Reagent (GE Healthcare) on ChemiDoc Imaging System (BioRad) using automatic detection settings.

Quantification and statistical analysis

Poly(A) tail length profiling

The NanoTail package [66] was used to perform the statistical analysis. The p-values were calculated using the Wilcoxon signed-rank test for transcripts represented by 10 or more reads, and adjustment for multiple comparisons was applied using the Benjamini-Hochberg method. Cohen d was used as an effect size measure. For values $x<0.2$, effect size was considered 'negligible', for values $0.2 \leq x<0.5$ it was considered 'small', for values $0.5 \leq x<0.8$ it was considered 'medium', and for values $x \geq 0.8$, it was considered 'large'. Transcripts were

considered significantly altered in poly(A) tail length if the adjusted p-value was less than 0.05 and the difference in tail length was greater than 5 nt between the hemispheres.

Alternative polyadenylation

Differential usage of poly(A) sites was calculated using two-sided Fisher's exact test. P-values were adjusted using the Benjamini-Hochberg method (given APA site was considered as differentially expressed if adjusted p-value was less or equal to 0.1).

Data visualization

The visualization of the data was performed in the R environment. Poly(A) nucleotide composition analyses using Ninetails [23]. Heatmaps were created with ComplexHeatmap [60], and genome browser-like diagrams were drawn using ggcoverage [71]. The remaining diagrams were created using ggplot2 [62].

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Author contributions

NG supervised by PK performed all the bioinformatic analyses and prepared figure drafts; FPP supported by PUG performed *in vivo* LTP. BK, PW and JM analyzed RNA samples and performed experiments on synaptoneurosomes. SM and SJ were responsible for nanopore sequencing. NG, FPP, AD, and MD wrote the manuscript. CRB, AD, and MD jointly supervised and directed the studies.

Declaration of interest

The authors declare no competing interests.

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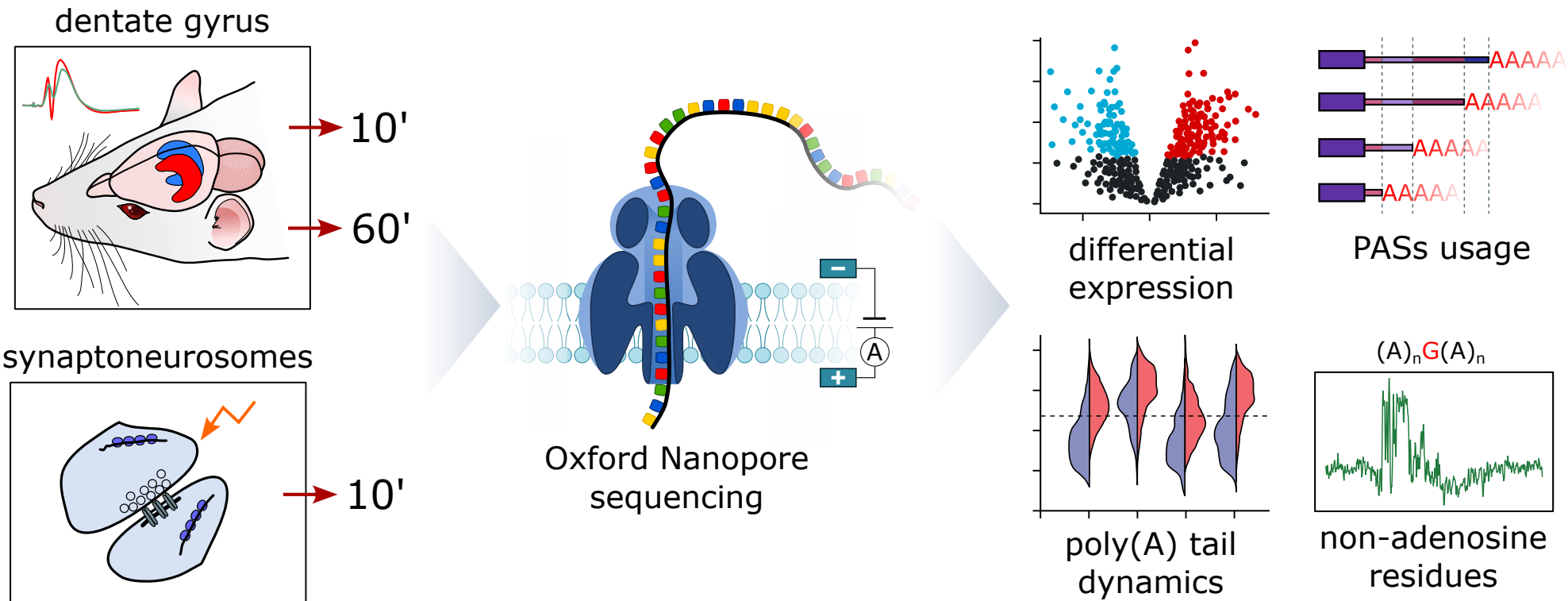
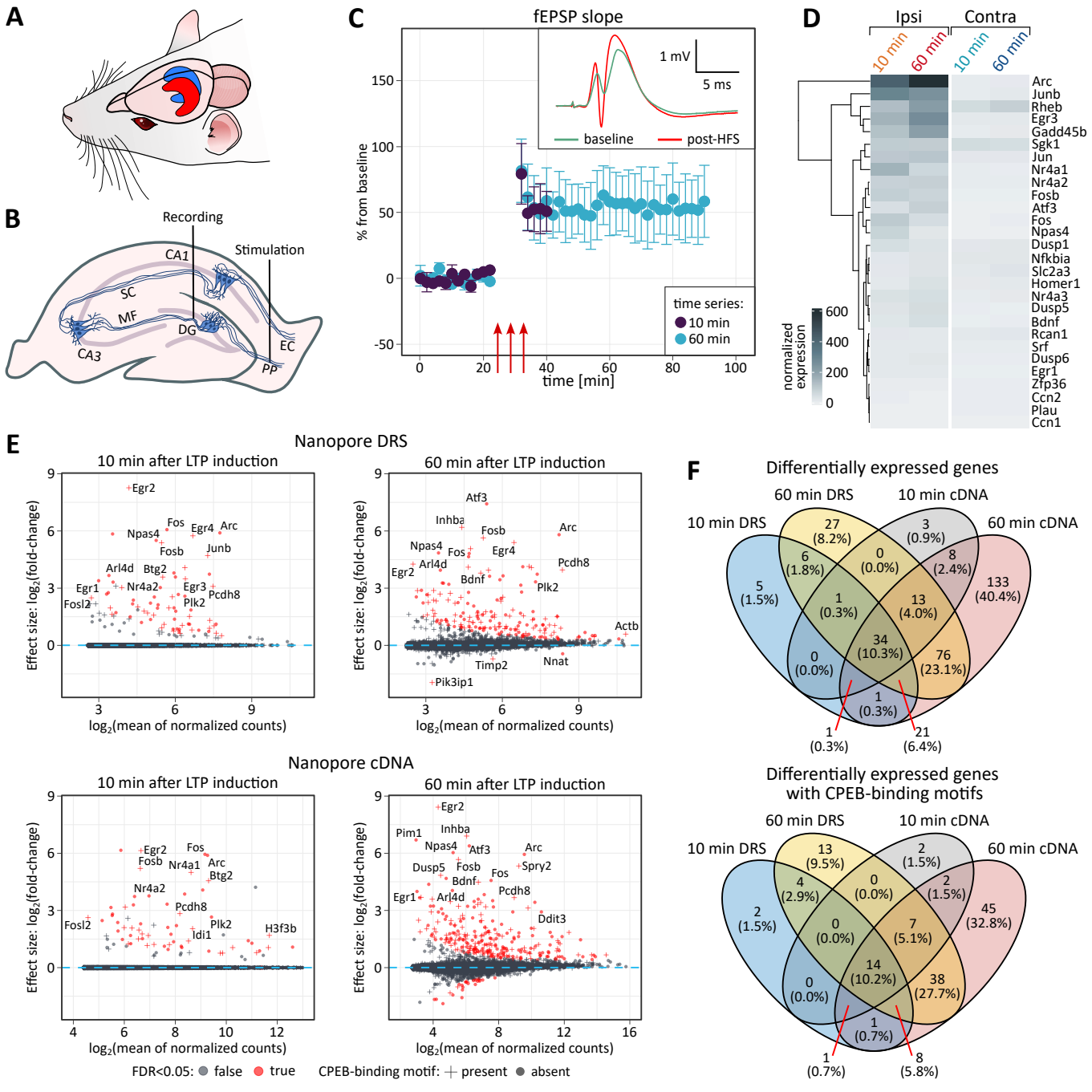
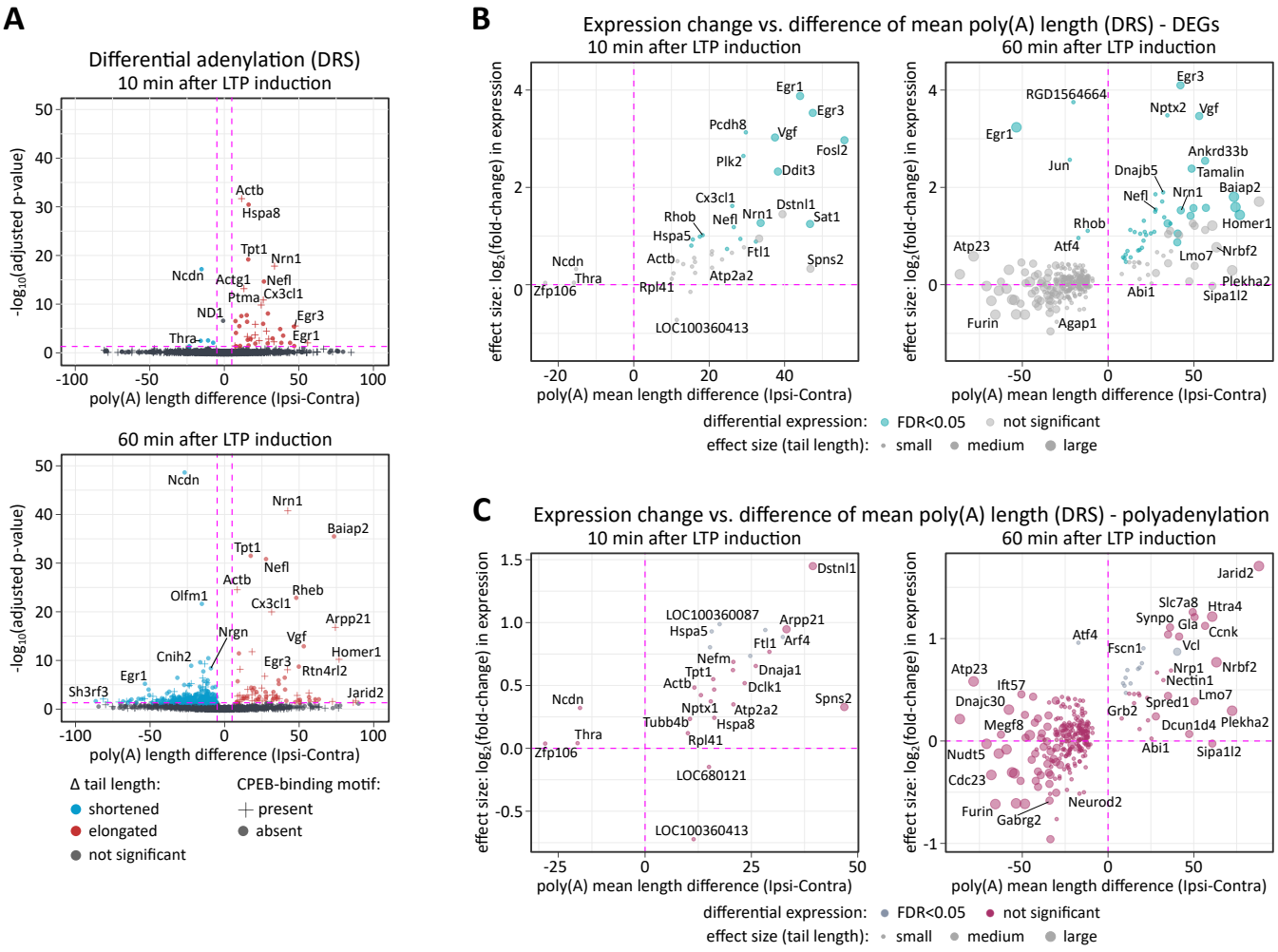
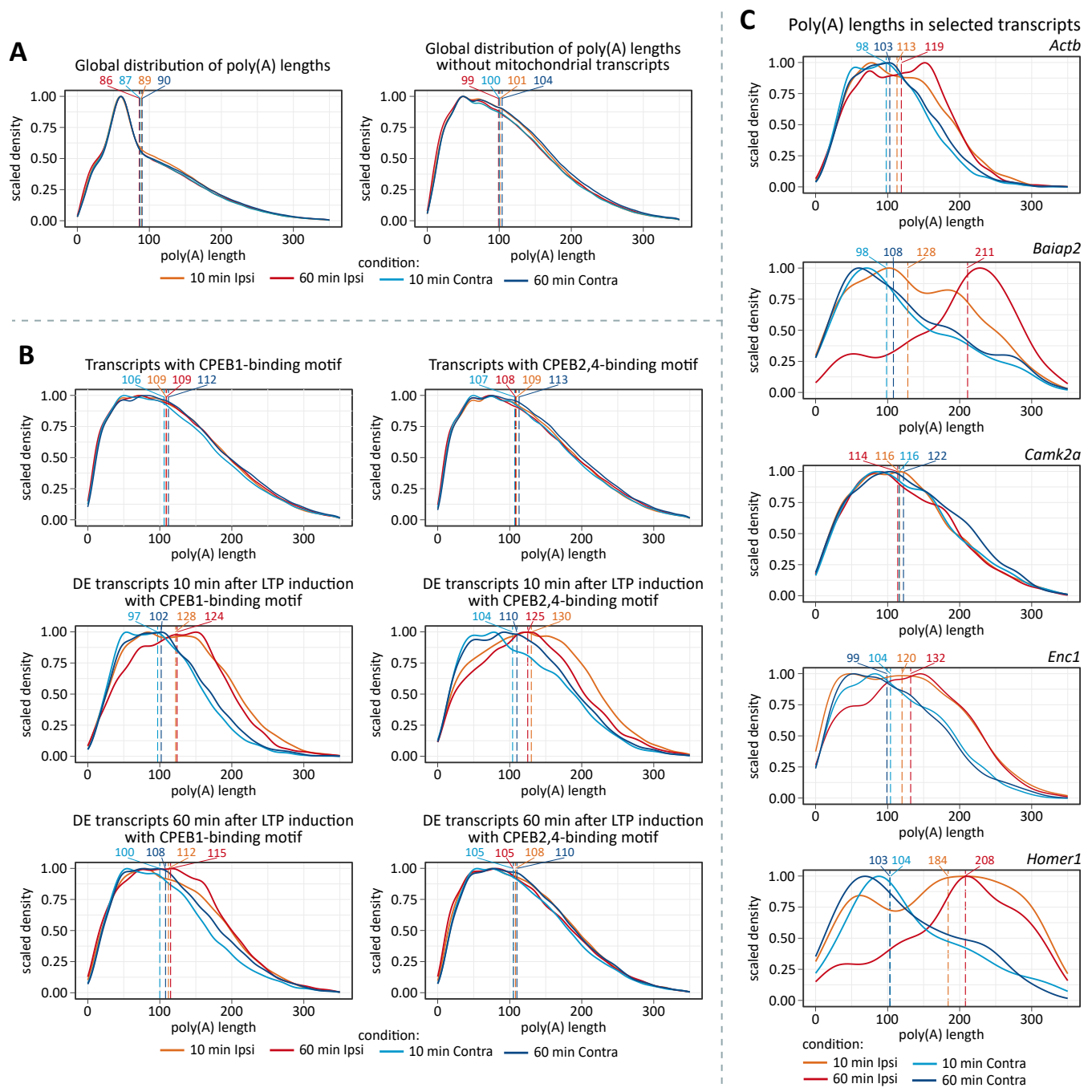
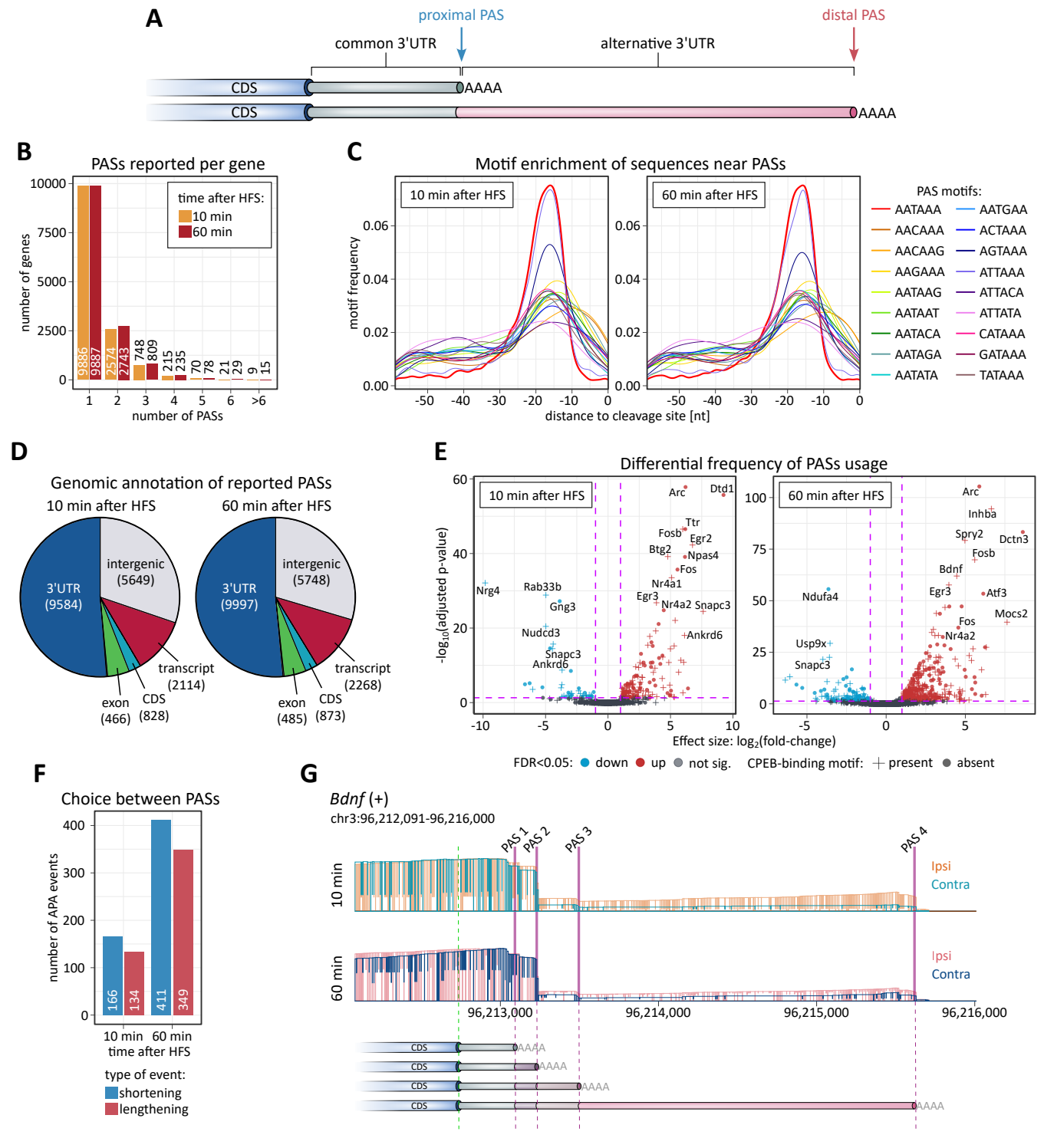
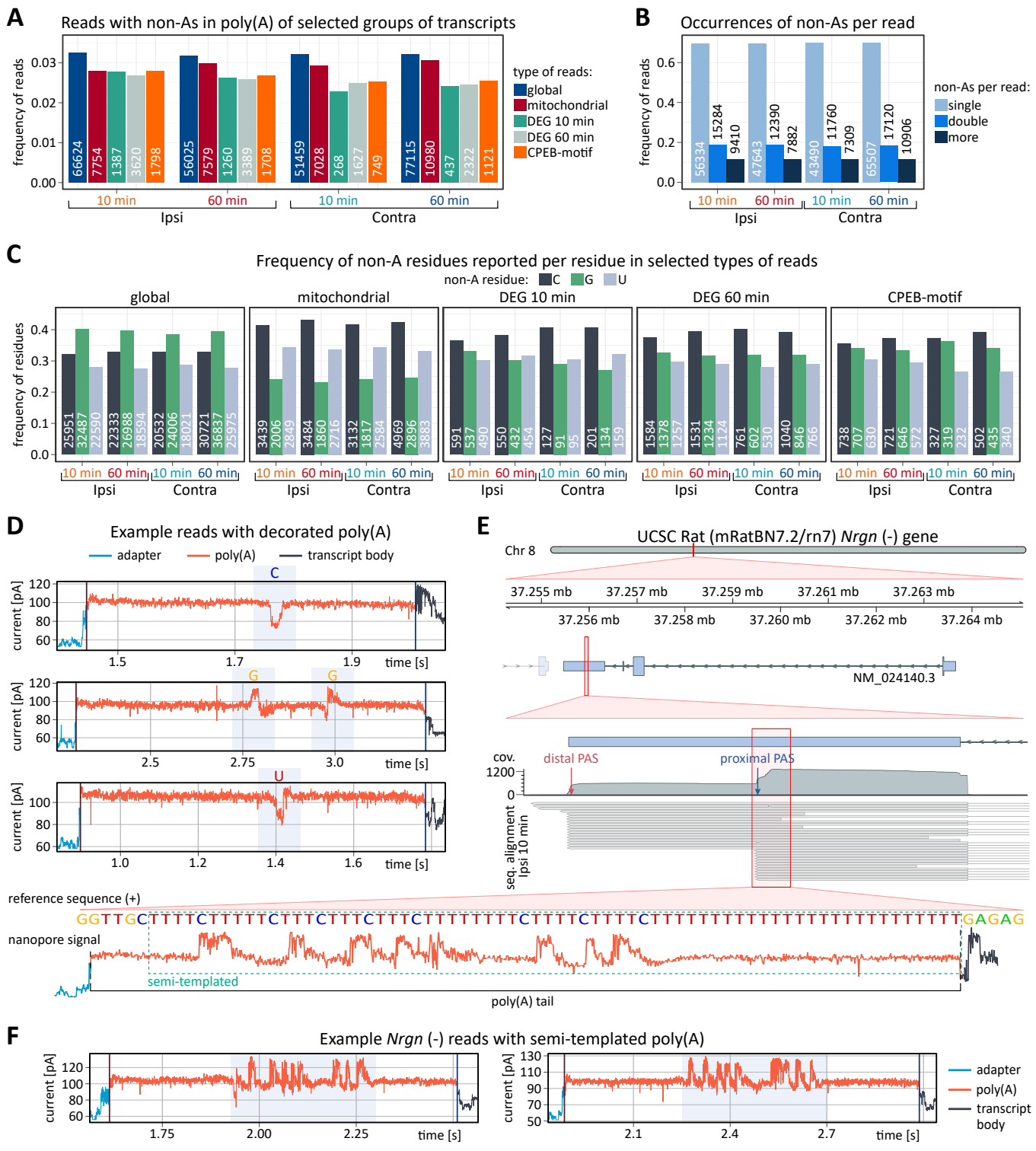

dentate gyrus
10'
60'
synaptoneurosomes
10'
Oxford Nanopore sequencing
differential expression
PASs usage
poly(A) tail dynamics
$(A)_nG(A)_n$
non-adenosine residues

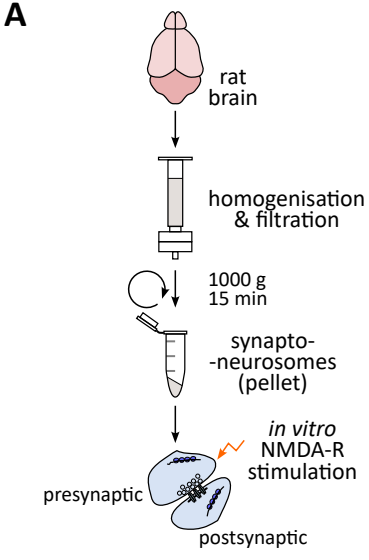

A
B
Recording
Stimulation
CA1
SC
MF
DG
CA3
EC
PP
C
fEPSP slope
1 mV
5 ms
baseline
post-HFS
% from baseline
time [min]
time series:
10 min
60 min
D
Ipsi
Contra
10 min
60 min
Arc
Junb
Rheb
Egr3
Gadd45b
Sgk1
Jun
Nr4a1
Nr4a2
Fosb
Atf3
Fos
Npas4
Dusp1
Nfkbia
Slc2a3
Homer1
Nr4a3
Dusp5
Bdnf
Rcan1
Srf
Dusp6
Egr1
Zfp36
Ccn2
Plau
Ccn1
normalized expression
E
Nanopore DRS
10 min after LTP induction
60 min after LTP induction
Effect size: log2(fold-change)
log2(mean of normalized counts)
Nanopore cDNA
FDR<0.05: false true
CPEB-binding motif: present absent
F
Differentially expressed genes
60 min DRS
10 min cDNA
10 min DRS
60 min cDNA
Differentially expressed genes with CPEB-binding motifs

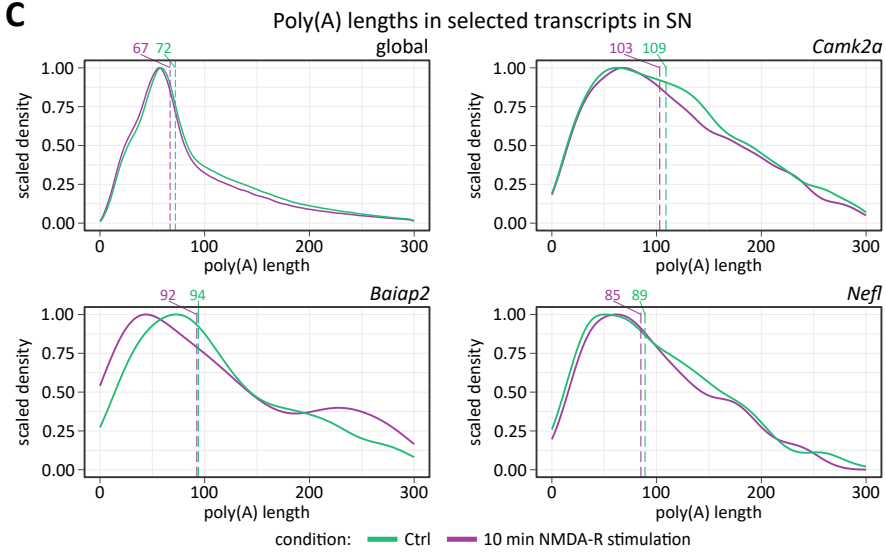

A
Differential adenylation (DRS)
10 min after LTP induction
-log10(adjusted p-value)
poly(A) length difference (Ipsi-Contra)
Actb
Hspa8
Tpt1
Nrn1
Ncdn
Actg1
Nefl
Ptma
Cx3cl1
ND1
Egr3
Egr1
Thra
60 min after LTP induction
Ncdn
Nrn1
Baiap2
Tpt1
Nefl
Actb
Olfm1
Rheb
Cx3cl1
Arpp21
Nrgn
Vgf
Cnih2
Homer1
Egr3
Rtn4rl2
Egr1
Sh3rf3
Jarid2
Δ tail length:
shortened
elongated
not significant
CPEB-binding motif:
present
absent
B
Expression change vs. difference of mean poly(A) length (DRS) - DEGs
10 min after LTP induction
60 min after LTP induction
effect size: log2(fold-change) in expression
poly(A) mean length difference (Ipsi-Contra)
Egr1
Egr3
Pcdh8
Vgf
Fosl2
Plk2
Ddit3
Cx3cl1
Dstnl1
Rhob
Nefl
Nrn1
Sat1
Hspa5
Ftl1
Ncdn
Actb
Spns2
Thra
Atp2a2
Zfp106
Rpl41
LOC100360413
RGD1564664
Nptx2
Vgf
Egr1
Ankrd33b
Jun
Tamalin
Dnajb5
Baiap2
Nefl
Nrn1
Rhob
Homer1
Atp23
Atf4
Lmo7
Nrbf2
Plekha2
Abi1
Sipa1l2
Furin
Agap1
differential expression:
FDR<0.05
not significant
effect size (tail length):
small
medium
large
C
Expression change vs. difference of mean poly(A) length (DRS) - polyadenylation
10 min after LTP induction
60 min after LTP induction
effect size: log2(fold-change) in expression
poly(A) mean length difference (Ipsi-Contra)
Dstnl1
LOC100360087
Arpp21
Hspa5
Ftl1
Arf4
Nefm
Tpt1
Dnaja1
Actb
Dclk1
Ncdn
Spns2
Nptx1
Atp2a2
Tubb4b
Hspa8
Thra
Rpl41
Zfp106
LOC680121
LOC100360413
Jarid2
Slc7a8
Htra4
Synpo
Gla
Ccnk
Atf4
Vcl
Fscn1
Atp23
Nrp1
Nrbf2
Ift57
Nectin1
Dnajc30
Lmo7
Spred1
Grb2
Megf8
Dcun1d4
Plekha2
Nudt5
Abi1
Sipa1l2
Cdc23
Neurod2
Furin
Gabrg2
differential expression:
FDR<0.05
not significant
effect size (tail length):
small
medium
large

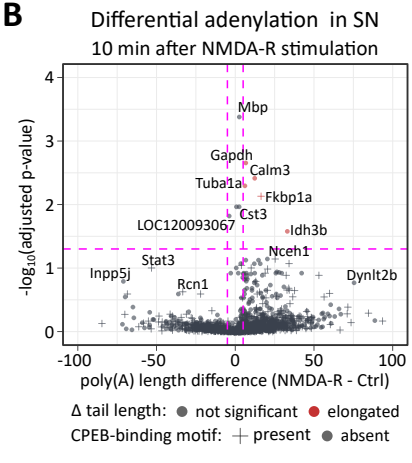

A
Global distribution of poly(A) lengths
86 87 89 90
Global distribution of poly(A) lengths without mitochondrial transcripts
99 100 101 104
scaled density
poly(A) length
condition:
10 min Ipsi
60 min Ipsi
10 min Contra
60 min Contra
B
Transcripts with CPEB1-binding motif
106 109 109 112
Transcripts with CPEB2,4-binding motif
107 108 109 113
DE transcripts 10 min after LTP induction with CPEB1-binding motif
97 102 128 124
DE transcripts 10 min after LTP induction with CPEB2,4-binding motif
104 110 125 130
DE transcripts 60 min after LTP induction with CPEB1-binding motif
100 108 112 115
DE transcripts 60 min after LTP induction with CPEB2,4-binding motif
105 105 108 110
C
Poly(A) lengths in selected transcripts
Actb
98 103 113 119
Baiap2
98 108 128 211
Camk2a
114 116 116 122
Enc1
99 104 120 132
Homer1
103 104 184 208

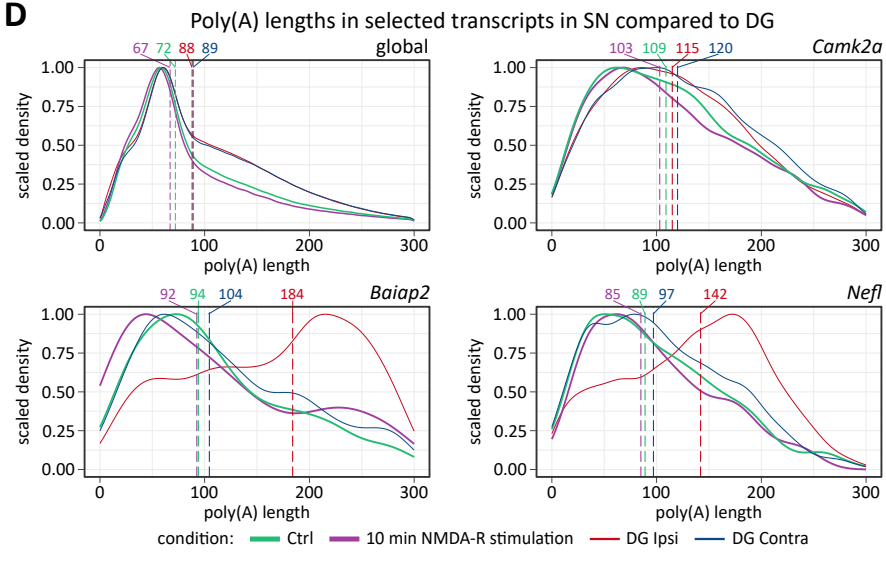

A
proximal PAS
distal PAS
common 3'UTR
alternative 3'UTR
CDS
AAAA
CDS
AAAA
B
PASs reported per gene
time after HFS:
10 min
60 min
number of genes
number of PASs
9886
9887
2574
2743
748
809
215
235
70
78
21
29
9
15
C
Motif enrichment of sequences near PASs
10 min after HFS
60 min after HFS
motif frequency
distance to cleavage site [nt]
PAS motifs:
AATAAA
AATGAA
AACAAA
ACTAAA
AACAAG
AGTAAA
AAGAAA
ATTAAA
AATAAG
ATTACA
AATAAT
ATTATA
AATACA
CATAAA
AATAGA
GATAAA
AATATA
TATAAA
D
Genomic annotation of reported PASs
10 min after HFS
60 min after HFS
3'UTR (9584)
intergenic (5649)
transcript (2114)
CDS (828)
exon (466)
3'UTR (9997)
intergenic (5748)
transcript (2268)
CDS (873)
exon (485)
E
Differential frequency of PASs usage
10 min after HFS
60 min after HFS
-log10(adjusted p-value)
Effect size: log2(fold-change)
Arc
Dtd1
Ttr
Fosb
Egr2
Btg2
Npas4
Fos
Nr4a1
Egr3
Nr4a2
Snapc3
Ankrd6
Nrg4
Rab33b
Gng3
Nudcd3
Snapc3
Ankrd6
Inhba
Spry2
Dctn3
Fosb
Bdnf
Egr3
Atf3
Mocs2
Fos
Nr4a2
Ndufa4
Usp9x
Snapc3
FDR<0.05: down up not sig. CPEB-binding motif: present absent
F
Choice between PASs
number of APA events
166
134
411
349
10 min
60 min
time after HFS
type of event:
shortening
lengthening
G
Bdnf (+)
chr3:96,212,091-96,216,000
PAS 1
PAS 2
PAS 3
PAS 4
10 min
60 min
Ipsi
Contra
Ipsi
Contra
96,213,000
96,214,000
96,215,000
96,216,000
CDS
AAAA


A
Reads with non-As in poly(A) of selected groups of transcripts
frequency of reads
0.03
0.02
0.01
0.00
66624
7754
1387
3620
1798
56025
7579
1260
3389
1708
51459
7028
268
1627
749
77115
10980
437
2322
1121
10 min
60 min
10 min
60 min
Ipsi
Contra
type of reads:
global
mitochondrial
DEG 10 min
DEG 60 min
CPEB-motif
B
Occurrences of non-As per read
frequency of reads
0.6
0.4
0.2
0.0
56334
15284
9410
47643
12390
7882
43490
11760
7309
65507
17120
10906
10 min
60 min
10 min
60 min
Ipsi
Contra
non-As per read:
single
double
more
C
Frequency of non-A residues reported per residue in selected types of reads
non-A residue:
C
G
U
global
mitochondrial
DEG 10 min
DEG 60 min
CPEB-motif
frequency of residues
0.4
0.3
0.2
0.1
0.0
25951
32487
22590
22333
26988
18594
20532
24006
18021
30721
36837
25975
3439
2006
2849
3484
1860
2716
3132
1817
2584
4969
2896
3883
591
337
490
550
432
454
127
91
95
201
134
159
1584
1378
1257
1531
1234
1124
761
602
530
1040
846
766
738
707
630
721
646
572
327
319
232
502
435
340
10 min
60 min
Ipsi
Contra
D
Example reads with decorated poly(A)
adapter
poly(A)
transcript body
C
G
G
U
current [pA]
120
100
80
60
1.5
1.7
1.9
2.5
2.75
3.0
1.0
1.2
1.4
1.6
time [s]
E
UCSC Rat (mRatBN7.2/rn7) Nrgn (-) gene
Chr 8
37.255 mb
37.257 mb
37.259 mb
37.261 mb
37.263 mb
37.256 mb
37.258 mb
37.260 mb
37.262 mb
37.264 mb
NM_024140.3
cov.
1200
0
distal PAS
proximal PAS
seq. alignment
Ipsi 10 min
reference sequence (+)
GGTTGCTTTTCTTTTTCTTTCTTTCTTTCTTTTTTTTCTTTTCTTTTCTTTTTTTTTTTTTTTTTTTTTTTTTTTTGAGAG
nanopore signal
semi-templated
poly(A) tail
F
Example Nrgn (-) reads with semi-templated poly(A)
current [pA]
120
100
80
60
1.75
2.00
2.25
time [s]
130
110
90
70
50
2.1
2.4
2.7
time [s]
adapter
poly(A)
transcript body


A
rat
brain
homogenisation
& filtration
1000 g
15 min
synapto-
-neurosomes
(pellet)
in vitro
NMDA-R
stimulation
presynaptic
postsynaptic


C
Poly(A) lengths in selected transcripts in SN
global
Camk2a
Baiap2
Nefl
67 72
103 109
92 94
85 89
scaled density
poly(A) length
condition: Ctrl 10 min NMDA-R stimulation


B
Differential adenylation in SN
10 min after NMDA-R stimulation
Mbp
Gapdh
Calm3
Tuba1a
Fkbp1a
Cst3
LOC120093067
Idh3b
Nceh1
Stat3
Inpp5j
Rcn1
Dynlt2b
-log10(adjusted p-value)
poly(A) length difference (NMDA-R - Ctrl)
Δ tail length: not significant elongated
CPEB-binding motif: present absent


D
Poly(A) lengths in selected transcripts in SN compared to DG
global
Camk2a
Baiap2
Nefl
67 72 88 89
103 109 115 120
92 94 104 184
85 89 97 142
scaled density
poly(A) length
condition: Ctrl 10 min NMDA-R stimulation DG Ipsi DG Contra