A microprocessor control system and solid state interface for controlling electrophysiological studies of conditioning

PAUL R. SOLOMON

Department of Psychology, Williams College, Williamstown, Massachusetts 01267

DONALD J. WEISZ, GREGORY A. CLARK, and JOHN HALL

Department of Psychobiology, University of California, Irvine, California 92717

and

BRYCE A. BABCOCK

Department of Physics, Williams College, Williamstown, Massachusetts 01267

This paper describes a microprocessor control system and solid state interface for controlling the apparatus in combined behavioral-electrophysiological studies of conditioning. The computer program, which is designed to control classical conditioning of the rabbit's nictitating membrane response, provides the flexibility to control all conditioning parameters (e.g., interstimulus and intertrial intervals, trial type, and sequence of trial types) with only minor modifications. The system is free from artifacts that can distort electrophysiological recordings and can easily be modified to accommodate other behavioral paradigms in which electrophysiological responses are recorded.

Electrophysiological recording of neural activity from awake, behaving animals has become a widely used method for investigation of physiological bases of behavior. We have designed a programmable, computer-controlled system, with a solid state interface to the experimental apparatus, for conducting behavioral studies that involve recording of electrophysiological activity. The system is flexible, inexpensive, and free from electrical artifacts that can distort electrophysiological recordings. Although our system is designed for electrophysiological studies of rabbit neural activity during classical conditioning of the nictitating membrane response (NMR), other behavioral paradigms can easily be accommodated.

THE PARADIGM

The paradigm for classical conditioning of the rabbit NMR is a modification of that initially described by Gormezano (1966). In our paradigm, the conditioned stimulus (CS) has a duration of 350 msec, the uncondi-

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Table 1
Timing Sequence for Variable ITI During Paired Training

Memory Location	Memory Contents	Number of Cycles	Time	Total ITI
0310	B0	176	46	50
0311	FD	253	66	70
0312	CB	203	53	57
0313	F5	245	64	68
0314	DE	222	58	62
0315	CF	207	54	58
0316	EA	234	61	65
0317	DA	218	57	61
0318	B8	184	48	52

Note—Time = time (in seconds) from previous trial offset to given trial onset, determined by memory contents. Total ITI = time (in seconds) from previous trial onset to given trial onset (i.e., includes 3.7 sec of within-trial time). Mean ITI = 60 sec (range = 50-70 sec); 1 cycle = 260.1 msec.

tioned stimulus (UCS) has a duration of 100 msec, and the interstimulus interval (ISI) is 250 msec. The intertrial interval (ITI) ranges between 50 and 70 sec, with a mean of 60 sec (Table 1). A typical conditioning session consists of 117 such trials divided into 13 blocks of 9 trials each. The first trial in each block is a CS-alone probe trial, and the remaining eight trials are composed of CS-UCS pairings.

As a control procedure for the electrophysiological studies, an explicitly unpaired program (see Rescorla,

Table 2
Timing Sequence for Variable ITI During Unpaired Training

Memory Location	Memory Contents	Number of Cycles	Time	Total ITI
0320	4D	77	20	24
0321	8A	138	36	40
0322	50	80	21	25
0323	73	115	30	34
0324	45	69	18	22
0325	67	103	27	50
0326	77	119	31	35
0327	7E	126	33	37
0328	6B	107	28	32
0329	6B	107	28	32
032A	3D	61	16	20
032B	7E	126	33	37
032C	58	88	23	27
032D	86	134	35	39
032E	64	100	26	30
032F	54	84	22	26
0330	86	134	35	28
0331	49	73	19	40
0332	50	80	21	22
0333	6B	107	28	25
0334	6F	111	29	33
0335	5C	92	24	28
0336	8A	38	36	40
0337	49	73	19	23
0338	73	115	30	34
0339	G4	100	26	30
033A	45	69	18	22
033B	6F	111	29	33
033C	7E	126	33	37
033D	41	65	17	21
033E	64	100	26	30
033F	6F	111	29	33

Note—Time = time (in seconds) from previous trial offset to given trial onset, determined by memory contents. Total ITI = time (in seconds) from previous trial onset to given trial onset (i.e., includes 3.7 sec of within-trial time). Mean ITI = 30 sec (range = 20-40 sec); 1 cycle = 260.1 msec. Memory contents are in hexadecimal (Base 16) in this and all subsequent tables.

1967) is used. In this paradigm, either the CS or the UCS is presented on a particular trial, but the two stimuli are never paired. The unpaired paradigm is run in blocks of 32 trials in which the CS and UCS are presented equal numbers of times in an unsystematic order. A conditioning session consists of 6.5 such blocks, for a total of 208 trials. The intertrial interval ranges from 20 to 40 sec, with a mean of 30 sec (Table 2).

THE KIM-1

The KIM microcomputer is a single-board microcomputer marketed by MOS Technology (division of Commodore Business Machines).¹ The KIM is based on the 6502 microprocessor and has been used in a variety of situations both to control the delivery of stimuli and to aid in data collection (Criswell & Babcock, 1978; Murray & Lawler, 1978; Parks, 1978). It has a calculator-type keypad for operator input with a six-digit LED display for output. A compact but versatile operating system resides in 2 KB of read-only memory (ROM)

contained on two 6530 peripheral interface/memory devices. These also contain two user-accessible interval timers and 15 programmable input/output lines for external sensing and control. Random-access memory (RAM) of 1 KB is available on board for program and data storage. There are hardware routines for cassette tape data storage and retrieval and operation from an external terminal. Although the present program was developed for use with the KIM-1, it is easily adaptable to other microprocessors (e.g., the SYM-1 by Synertek and the Rockwell AIM-65).

THE PROGRAM

A computer program for classical conditioning of the rabbit's NMR must be capable of controlling a variety of events. In addition to controlling the delivery of the conditioned and unconditioned stimuli, the program must operate a polygraph and a tape recorder that are used for collecting and analyzing the electrophysiological and behavioral data. The program must also deliver a series of three synchronizing pulses that serve as event markers. The first pulse occurs 250 msec prior to the CS onset and denotes the pre-CS period, which is used to sample baseline neural activity. The last two pulses coincide with delivery of the CS and the UCS. The pulses are used for subsequent computer analysis of the data (see Roemer, Cegavske, Thompson, & Patterson, 1975).

The present program (Figure 1, Table 3) is an expanded version of that reported by Solomon and Babcock

Figure 1. KIM program flowchart.

Table 3
KIM NMR Conditioning Routine

Variable Declaration				Programs			
Memory Location	Variable	Address	Comments	Memory Location	HEX Code	Statement Labels	Operation Comments
02001	2	005	00200 :PROGRAM ORIGIN	02001A9 FF	42	BEGIN	LDA #*FF :START OF PROGRAM
00001	3	TIMCNT	EDU #0000 :TABLE OF TIMING LOOP VALUES	02001BD 01	17	STA FADD	:SET JIM FORT A FOR OUTPUT
00101	4	TUNIT	EDU #0010 :TABLE OF TIMING BASE VALUES	02001A9 00	44	LDA #*00	:CLEAR TRIAL COUNTER
00201	5	FOUT	EDU #0020 :PAIRED OUTPUT TABLE	02001B5 50	45	STA TRLCNT	:STA TRLCNT
00301	6	CSOUT	EDU #0030 :CS OUTPUT TABLE	02001A9 00	46	LDA #*00	:CLEAR CYCLE COUNTER
00401	7	USOUT	EDU #0040 :US OUTPUT TABLE	02001B5 50	47	STA CYCNT	:STA CYCNT
00501	8	TRLCNT	EDU #0050 :TRIAL COUNTER	02001A2 00	48	STRTRL LDX #00	:START NEW TRIAL
00511	9	TRLCPTR	EDU #0051 :INDIRECT POINTER FOR OUTPUT TABLE	02001F	49	*	:INITIALIZE TRIAL INDEX (XREG)
00601	10	CYCNCNT	EDU #0060 :CYCLE COUNTER	02001A0 50	50	LDY #*50	:USE TRIAL COUNT FOR TABLE ACCESS
03001	11	SEQ	EDU #0200 :SEQUENCE TABLE	02111B7 10 00	51	LDA FVITLY	:FETCH VARIABLE ITI TIMING VALUE
03101	12	PVITI	EDU #0310 :PAIRED VARIABLE ITI TABLE	02111B5 00	52	STA TIMCNT	:STORE IN TIMING LOOP TABLE
03201	13	UFVITI	EDU #0320 :UNPAIRED VARIABLE ITI TABLE	02111B4 00	53	LDY TIMCNT,X	:SET TIMING COUNT
17001	14	PAD	EDU #1700 :OUTPUT REGISTER A	02111B5 10	54	BASELP	LDA TUNIT,X :SET TIMING UNIT
17011	15	PADD	EDU #1701 :DATA DIRECTION REGISTER A				
17021	16	PBD	EDU #1702 :OUTPUT REGISTER B	02111B8 07 17	55	STA TIMER	:START 1024MS TIMER
17031	17	PDD	EDU #1703 :DATA DIRECTION REGISTER B	02111C2 07 17	56	CHITIM BIT	CHITIM :WAIT FOR COMPLETION OF TIME UNIT
17071	18	TIMER	EDU #1707 :1024USEC TIMER REGISTER	0220110 FR	57	BFL CHITIM	
1C001	19	MONITR	EDU #1C00 :JIM MONITOR SOFT ENTRY	02201B8	58	DEY	:DECREMENT TIMING COUNT
17FA1	20	NMI	EDU #17FA :NONMASKABLE INTERRUPT VECTOR (ST+EV)	02201D0 F0	59	BNE BASELP	:LOOP UNTIL COUNT IS ZERO
17FC1	21	RST	EDU #17FC :RESET VECTOR (POWER UP)	02201B8	60	CLC	:DETERMINE TRIAL TYPE FROM SEQ. TABLE
17FE1	22	IRQ	EDU #17FE :INTERUPT VECTOR (LOCAL COMMANDS)	02201BA	61	TXA	
1F1F1	23	SCANDS	EDU #1F1F :KEYBOARD DISPLAY ROUTINE	0227171 50	62	ADC (TRLCNT),Y	
02001	24	*		02271AA	63	TAX	
02001	25	*	FORMAT OF TRIAL SUBINTERVALS -	02201EA	64	NOP	
02001	26	*		02201B5 20	65	LDA	FOUT,X :LOAD OUTPUT REG. FROM OUTPUT TABLE
02001	27	*	DEC (HEX) - EVENT	02201BD 00 17	66	STA FAD	
02001	28	*		02201BA	67	TXA	:RESET TRIAL INDEX
02001	29	*	00 (00) - COUNTER	0221120	68	SEC	
02001	30	*	01 (01) - TAPE + POLY	02221F1 50	69	SBC (TRLCNT),Y	
02001	31	*	02 (02) - TAPE + POLY + PCS SYNC	02231AA	70	TAX	
02001	32	*	03 (03) - TAPE + POLY	02231EB	71	INX	
02001	33	*	04 (04) - TAPE + POLY + TONE + CS SYNC	02241E0 00	72	CPX #12	:CHECK IF FINAL EVENT
02001	34	*	05 (05) - TAPE + POLY + TONE	0224190 00	73	BCC TIMELP	:LOOP UNTIL TRIAL COMPLETE
02001	35	*	06 (06) - TAPE + POLY + TONE + AIR	02241E6 50	74	INC TRLCNT	:INCREMENT TRIAL COUNT
02001	36	*	07 (07) - TAPE + POLY + TONE + AIR + UCSSYNC	02251A5 50	75	LDA TRLCNT	
02001	37	*	08 (08) - TAPE + POLY + TONE + AIR	02261C9 09	76	CMF #9	:CHECK FOR COMPLETION OF 9 TRIALS
02001	38	*	09 (09) - TAPE + POLY + TONE	0240190 CB	77	BCC STRTRL	:TAKE NEXT TRIAL IF NOT FINISHED
02001	39	*	10 (0A) - TAPE + POLY	02421A9 00	78	LDA #00	:CLEAR TRIAL COUNTER
02001	40	*	11 (0B) - ALL OFF (ITI)	02441B5 50	79	STA TRLCNT	
02001	41	*		02461E6 60	80	INC CYCNCNT	:INCREMENT CYCLE COUNTER
				02461A5 60	81	LDA CYCNCNT	
				02461C9 0E	82	CMF #14	:CHECK FOR COMPLETION OF 13 BLOCKS
				0246190 FF	83	BCC STRTRL	:TAKE NEXT BLOCK IF NOT FINISHED
				024E190	84	BRK	:RETURN TO MONITOR

*** SUCCESSFUL ASSEMBLY: NO ERRORS

Note—Address 0051 (under "Variable Declaration") must be set to 03, the page number of the output tasks.

Table 4
Within-Trial Timing Values

Memory Location	Memory Contents	Event	Number of Cycles	Event Duration	Event Onset	K Value	Cycle Duration
Number of Cycles (Stored in Y Register)							
0000	*	ITI	†	†	2607		
0001	62	Counter	98	100			
0002	0A	Tape + Polygraph	10	1003			
0003	01	Tape + Polygraph + Tone + Pre-CS SP	1	1	0		
0004	F2	Tape + Polygraph	242	248	1		
0005	01	Tape + Polygraph + Tone + CS SP	1	1	249		
0006	D3	Tape + Polygraph + Tone	211	216	250		
0007	1F	Tape + Polygraph + Tone + Air	31	32	466		
0008	01	Tape + Polygraph + Tone + Air + UCS SP	1	1	498		
0009	43	Tape + Polygraph + Tone	67	69	499		
000A	20	Tape + Polygraph + Tone	32	33	567		
000B	14	Tape + Polygraph	20	2007	2574		
Length of Each Cycle							
0010	FE	ITI				254	260.1
0011	01	Counter				1	1.024
0012	62	Tape + Polygraph				98	100.4
0013	01	Tape + Polygraph + Pre-CS SP				1	1.024
0014	01	Tape + Polygraph				1	1.024
0015	01	Tape + Polygraph + Tone + CS SP				1	1.024
0016	01	Tape + Polygraph + Tone				1	1.024
0017	01	Tape + Polygraph + Tone + Air				1	1.024
0018	01	Tape + Polygraph + Tone + Air + UCS SP				1	1.024
0019	01	Tape + Polygraph + Tone				1	1.024
001A	01	Tape + Polygraph + Tone				1	1.024
001B	62	Tape + Polygraph				98	1.024

Note—The total duration of an event is actually determined by two variables: the cycle duration and the number of cycles. The cycle duration is determined by the K value, ranging from 1 to 254 (1.024-260.1 msec). The number of cycles (1-254) multiplied by the cycle duration then determines the total duration of the event (1.024 msec to 66.1 sec). Event and cycle durations are given in milliseconds. "Event onset" = the number of milliseconds after the pre-CS synch pulse; SP = synch pulse.

**Loop in program. †Variable.*

(1979), modified to include an explicitly unpaired conditioning procedure, as well as the additional timing events. The program times 12 separate events ranging in duration from 1 msec to 66 sec. At the conclusion of each timing interval, the KIM initiates an event. This is accomplished through the 15 input/output ports of the KIM board.

Three major types of variables are controlled by the KIM program: (1) timing value, the time for events within a trial (Table 4) or the time between trials (Table 1, paired program; Table 2, unpaired program); (2) the output command, which controls which events (e.g., CS delivery, UCS delivery, or both) occur on a particular type of trial (see Tables 5 and 6); and (3) the trial sequence, the choice of which type of trial (e.g., CS-alone, UCS-alone, or CS-UCS paired trial) will occur in the program sequence (Table 7, paired program; Table 8, unpaired program). Any of these variables can easily be changed by altering the contents of the relevant memory locations, allowing maximal flexibility.

Timing Values

The timing tables control the time between events such as tape recorder onset or stimulus delivery. During each trial, the program steps through 12 timing sequences (see Table 4 and Figure 1). The value for each of these times is stored in KIM memory in a timing table (Table 4 for within-trial values and Tables 1 and 2 for variable ITIs). In this way, the length of any event can be changed without affecting the remainder of the program by changing the contents of one memory location.

The timing values chosen for several events deserve special mention. First, the final stage of analysis on a PDP-12/PDP-11 computer system (Roemer et al., 1975) uses 3-msec time bins; therefore, we have chosen the onset (or offset) of the stimulus events to coincide with the onset (or offset) of 3-msec intervals. For example, the pre-CS to CS interval is 249 msec (not 250 msec).

A second point concerns the values chosen for the ITIs (Tables 1 and 2). We wish to set the interval from trial onset to next trial onset; however, the KIM times the interval between trial offset to next trial onset (i.e., it does not include the 3.7 sec of within-trial time). Accordingly, the KIM values are approximately 4 sec shorter than the desired ITIs (see Table 1).

Table 5
Output Commands for Paired, CS-Alone, and UCS-Alone Trials

ML	MC	Event
Paired Trials		
0020	04	Counter
0021	08	Tape + Polygraph
0022	28	Tape + Polygraph + Pre-CS SP
0023	08	Tape + Polygraph
0024	4A	Tape + Polygraph + Tone + CS SP
0025	0A	Tape + Polygraph + Tone
0026	1A	Tape + Polygraph + Tone + Air
0027	9A	Tape + Polygraph + Tone + Air + UCS SP
0028	1A	Tape + Polygraph + Tone + Air
0029	0A	Tape + Polygraph + Tone
002A	08	Tape + Polygraph
002B	00	All Off (ITI)
CS-Alone Trials		
0030	04	Counter
0031	08	Tape + Polygraph
0032	28	Tape + Polygraph + Pre-CS SP
0033	08	Tape + Polygraph
0034	4A	Tape + Polygraph + Tone + CS SP
0035	0A	Tape + Polygraph + Tone
0036	0A	Tape + Polygraph + Tone
0037	0A	Tape + Polygraph + Tone
0038	0A	Tape + Polygraph + Tone
0039	0A	Tape + Polygraph + Tone
003A	08	Tape + Polygraph
003B	00	All Off (ITI)
UCS-Alone Trials		
0040	04	Counter
0041	08	Tape + Polygraph
0042	28	Tape + Polygraph + Pre-CS SP
0043	08	Tape + Polygraph
0044	08	Tape + Polygraph
0045	08	Tape + Polygraph
0046	18	Tape + Polygraph + Air
0047	98	Tape + Polygraph + Air + UCS SP
0048	18	Tape + Polygraph + Air
0049	08	Tape + Polygraph
004A	08	Tape + Polygraph
004B	08	All Off (ITI)

Note—The manner in which these output command tables determine which stimuli are delivered is as follows. At the end of a programmed timing sequence, the microprocessor goes to the corresponding memory location in the output table and moves the contents of this location to Output Port A. (Although the KIM has two 8-bit output ports, only one is needed for this particular program.) Each bit in the output port controls one piece of apparatus (e.g., counter, tone generator, etc.), as indicated in Table 6. ML = memory location, MC = memory contents, and SP = synch pulse.

Table 6
Output Port A (Memory Location 1700)

Memory Location	Memory Contents	Event	Synch Pulse				Tape + Polygraph	Counter	Tone	Open
			UCS	CS	Pre-CS	Air				
0020	04	Counter	0	0	0	0	0	1	0	0

Note—A "1" in any location represents a 5-V output pulse that, through the interface, turns on the apparatus to which the bit is connected. For example, our trial counter is connected to the third output bit; an "04" in hexadecimal indicates that this bit is high (+5 V) and all others are low (0 V). Thus, at the end of the ITI timing sequence in the paired trial, the KIM-1 accesses Memory location 0020, moves the memory contents (04) to Output Port A (Memory Location 1700), and thereby turns on the counter.

The final consideration concerns the time at which the airpuff solenoid is activated. To compensate for the extra time necessary for the compressed air to travel through the Tygon tubing from solenoid to cornea, the solenoid must be activated before the desired time of airpuff delivery (see Figure 2). The arrival of the airpuff (and hence, delay time) can be accurately measured by holding the end of the Tygon tube to an open lead of an amplifier or to a BNC terminal on a high-gain oscilloscope. In our apparatus, the delay from solenoid activation to airpuff arrival at cornea is approximately 32 msec. However, this value varies according to tubing length and must be empirically determined for each case.

Output Commands

At the conclusion of each timing loop, the program points to one of three tables that contain output commands (see Table 5). These tables determine the stimuli to be delivered on a given type of trial. In the paired paradigm, there are two output tables that can be accessed. The first contains output commands for paired CS-UCS trials, and the second contains commands for the CS-alone trials. The unpaired paradigm also makes use of the CS-alone output table, as well as a third output table that controls UCS-alone trials.

Trial Sequence

Finally, to determine the output table to be accessed, (i.e., which type of trial will occur), we use a trial sequence table for paired (Table 7) and unpaired (Table 8) paradigms. At the conclusion of each trial, the program points to one of the locations in the output sequence table. The contents of this location determines which of the three output tables (in Table 5) is accessed. In the present program, a 00 in any location will lead to

Figure 2. Timing values for each of the events in the conditioning paradigm.

Table 7
Trial Sequence for Paired Training

Memory Location	Memory Contents	Trial Number	Trial Type
0300	10	1	CS
0301	00	2	P
0301	00	3	P
0303	00	4	P
0304	00	5	P
0305	00	6	P
0306	00	7	P
0307	00	8	P
0308	00	9	P

Note—When computer points to Memory Location 0300, it adds the contents of this location to 0020 to determine the address of the first output command of the trial (Table 5). Thus, on paired trials, the output commands start at Memory Location 0020, on CS-alone trials at 0030, and on UCS-alone trials on 0040. By changing the contents of Memory Locations 0300-0308, any sequence of CS, UCS, and CS-UCS trials are possible, and by adding additional output tables, many different stimulus configurations are possible.

Table 8
Trial Sequence for Unpaired Training

Memory Location	Memory Contents	Trial Number	Trial Type
0300	10	1	CS
0301	20	2	UCS
0302	10	3	CS
0303	10	4	CS
0304	20	5	UCS
0305	10	6	CS
0306	20	7	UCS
0307	20	8	UCS
0308	20	9	UCS
0309	10	10	CS
030A	20	11	UCS
030B	10	12	CS
030C	20	13	UCS
030D	20	14	UCS
030E	10	15	CS
030F	10	16	CS
0310	20	17	UCS
0311	10	18	CS
0312	10	19	CS
0313	20	20	UCS
0314	20	21	UCS
0315	10	22	CS
0316	20	23	UCS
0317	10	24	CS
0318	10	25	CS
0319	10	26	CS
031A	20	27	UCS
031B	10	28	CS
031C	20	29	UCS
031D	20	30	UCS
031E	10	31	CS
031F	10	32	UCS

a CS-UCS trial, a 10 will produce a CS-alone trial, and a 20 will produce a UCS-alone trial. At the end of nine trials, which constitutes a block in our paradigm, the paired program recycles to the beginning of the sequence. The unpaired program recycles after 32 trials.

This system provides a high degree of flexibility. By altering the contents of the locations in the output sequence table and, if necessary, adding additional output tables, the user can obtain any combination of stimulus configurations within a block of trials. In addition, with minimal reprogramming (simply increasing the number of locations in the output sequence table), the user can change the number of trials and thus the possible stimulus configurations within a block of trials (e.g., for discrimination paradigms, see Solomon & Babcock, 1979). For example, in the paired program, we use one CS-alone trial followed by eight paired trials, for a total of nine trials per block. In the unpaired program, however, we use an unsystematic sequence of 32 CS-alone or UCS-alone trials. To accomplish this, the number of memory locations in the trial sequence table is increased to 32 (by changing the contents of Memory Location 023F from 09 to 20; see Table 8).

COMPATIBILITY WITH OTHER MICROPROCESSORS

While the KIM has become a much used laboratory instrument, its features have been extended by second generation boards, particularly the SYM-1 by Synertek and the AIM-65 by Rockwell.² All the features of our present conditioning control system can be implemented easily with either the SYM or AIM microcomputers. Both of these boards contain significantly enhanced standard features when compared to the KIM while allowing for considerable on-board expansion (including a BASIC language interpreter, an assembler, and up to 4 KB of RAM). The more expensive AIM-65 comes with a typewriter-style keyboard and a 20-column printer. Both of the second-generation boards have attempted to maximize compatibility with the existing KIM architecture. Software and hardware differences are generally noted in their literature, and suggestions are given for adapting KIM programs to their systems (see DeJong, 1980, for a comparison of the KIM, SYM, and AIM microprocessors).

The major area of difference, apart from the more sophisticated operating systems, lies with input and output. The input/output devices are located at different addresses and are initialized in slightly different ways. The SYM and AIM use 6522 versatile interface adapters instead of the 6530. Each 6522 has two interval timers, 16 input/output lines, and 4 "handshaking" lines. The interval timers are particularly powerful and can function as digital pulse generators and pulse counters.

The basic 6522 timer operation consists of presetting a 16-bit counter and decrementing it at the microprocessor clock rate until it reaches zero. The comparable KIM operation involves setting an 8-bit counter and decrementing it at the clock rate divided by 1, 8, 64, or 1,024. In the present system, the 1,024 rate provides a time scale in the 1-msec range. This can easily be emu-

lated on a SYM or AIM system by using the 6522 to time 1-msec intervals and adding an extra loop to the timing portion of the program to count these. The 6522 timers will run continuously at a preset rate, providing the equivalent of a real-time clock independent of program execution time. (The KIM timers must be reset by the program when they time out.)

Of course, these are not the only single-board microcomputers available that are capable of controlling a typical conditioning system. Several other systems using alternative microprocessors (1802, 6800, 8080, Z80, etc.) are available. We have stressed the 6502 family of microcomputer boards because of their similarity to the present system and the ease with which this system could be adapted (DeJong, 1980).

Smaller, "dedicated," microcomputer boards such as the John Bell Engineering 6502 are also fully capable of such control systems if provided with the appropriate program in electrically programmable memory (EPROM). Such dedicated boards do not have operator input and output via keyboard and display. They are programmed to perform a preset series of operations. Since this is typical of a standard conditioning system, these boards can provide a significant cost reduction in the case of redundant setups. In addition, they provide easy on-off use, simplifying operator training. EPROM programmers are available for use with most microcomputers, as well as ultraviolet lamps for erasing EPROMS so that they may be reused.³

Scandrett and Gormezano (1980) report a system that uses an Apple II to control the conditioning paradigm and to also collect and analyze analog data from the NMR. We recently developed a combined KIM-1 and Apple II system that not only controls the conditioning paradigm and collects analog data from the NMR, but also collects electrophysiological data, plots poststimulus histograms, and computes standard scores (Solomon, Babcock, & Gastell, Note 1). These Apple-based systems have many advantages, but they tend to be comparatively expensive (between \$4,000 and \$5,000 for a complete setup). A microprocessor-based system is capable of performing the same control functions and can be fully configured for less than \$500.

THE INTERFACE

The interface between the KIM-1 and the experimental apparatus minimizes electrical artifacts in the neural recordings. Figure 3 depicts the primary components of the interface. At the first stage of the interface, each KIM 5-V output is buffered by feeding the 5-V pulses into one gate of a Type 7406 TTL hex inverter driver. The outputs of the 7406 drivers switch the inputs of optical isolators (GE optical isolator Model H11B255).

Optoelectronic couplers provide an ideal means of isolating the computer and its associated power supplies from the physiological system under observation. This

Figure 3. Schematic diagram of interface between KIM and conditioning apparatus.

helps to eliminate ground loop and noise problems in the electronic circuitry, as well as eliminating possible unknown and unwanted electrical stimuli to the subject. The only disadvantage of such isolation is the time delay that signals experience in passing through optocouplers. For the isolation unit used in the present set-up, H11B255, the delays are of the order of 100 microsec. This provides no problems whatsoever for our conditioning system. In analyzing systems with significantly more rapid response, the 4N29-4N30 series of optocouplers is more appropriate (delays less than <50 microsec). (Optocouplers are available with delays less than 100 nanosec. Hewlett-Packard's 6N137 is such a device.)

The output of each optical isolator controls a transistor (2N3904). The type of connection made from the transistors depends on the characteristics of the electrical signals needed to operate various pieces of equipment. There are three possibilities. If the input to the piece of equipment is to the base of a transistor and the current is less than 200 mA, then the output of the 2N3904 can be connected directly to the equipment (Figure 3A).

A different type of situation arises when the power requirements of the experimental apparatus are greater than the capabilities of the 2N3904. If the apparatus requiring high power needs to be operated at a time when electrophysiological recordings are being made, we recommend that the 2N3904 output be connected to the base of a power transistor (e.g., 2N3441, Figure 3B). The power transistor should be attached to a heat sink

and enclosed in a small chassis box. We recommend that a diode be used to minimize transients. The control circuitry for the air solenoid (Figure 3B) is an example of this type of system.

If the apparatus requiring high power is turned on and off at times when no important information is being recorded, relays can be used in place of the power transistors (Figure 3C). Multiple-pole relays can be used if two or more circuits are switched on and off simultaneously; for example, a tape recorder and a polygraph can be operated simultaneously by a multiple-pole relay. We chose to provide an additional stage of isolation when driving relays by adding a second 2N3904 transistor and a diode. Thus, relay switching transients are further buffered from the optical isolation. The relay may be simpler to use than the power transistor, since the relay circuit does not require a heat sink.

An example will serve to illustrate how this circuit operates. Entering a "04" in Memory Location 1700 activates the output bit devoted to the trial counter (see Table 6); when the output bit goes high (+5 V), the 7406 driver goes low (0 V). This provides a "sink" for current through the LED in the optical isolator. This turns the LED on, which in turn activates the output phototransistor within the optical isolator. Since the phototransistor now conducts to ground, it robs the first 2N3904 of its base current, and the 2N3904 turns off. This turns on the second 2N3904. (Note that turning the transistor of one stage on turns the next transistor off, and vice versa.) Current can now flow through

Figure 4. Schematic diagram for generating synchronous pulses.

the solenoid to ground via the transistor, and the counter is activated. The logic is simply reversed when the KIM output bit goes low.

In order to minimize electrical artifacts, close attention must be paid to the ground circuits. We use one ground circuit with the KIM inputs, a second with the optical isolators, transistors, and synchronizing pulse circuits, and a chassis (earth) ground.

Since we are interested in time-locked events, synchronizing pulses must be generated. These pulses are used to signal to the computer when key events occur. There are two major considerations in designing the synchronizing pulse circuit: (1) shaping the pulses to make them compatible with direct audio recording, and (2) having pulses of different polarities and/or amplitudes to allow discrimination between them.

The circuit shown in Figure 4 meets both of these requirements. Timing of synch pulse delivery per se is determined by the program. The KIM output (5 V, 1-msec duration) controls one gate of a 7407 driver, which in turn initiates an output from an optical isolator. At this point, the pulses are shortened and shaped to prevent overshoot (with most audio systems, dc components cannot be recorded, and a long monophasic pulse will be recorded as a biphasic one). The width of the pulse was first shortened from 1.0 msec to approximately .1 msec using a dual monostable multivibrator (74123) as a simple timer. The inclusion of a potentiometer in the circuit allows greater flexibility in determining the width of the synch pulses. In addition, a capacitor is placed on the feedback of the summing circuit (described below) to shape pulse rise time, thereby eliminating the remaining (.1-msec) dc component.

The 74123 outputs are then sent into an op-amp circuit, which sums them. By varying the polarity and amplitude of the pulses, each stimulus event generates its own unique synch pulse. The polarity of the UCS synch pulse is inverted by the first op-amp; the pre-CS

and CS synch pulses bypass this stage, remaining positive. The second op-amp sums (and inverts) all three synch pulses. Amplitudes of the individual synch pulses can be varied by changing the input resistances. Using this circuit, three distinct synch pulses can be shaped: a negative pulse (−1 V), a large negative pulse (−2 V), and a large positive pulse (+2 V). The first signals trial onset, the second signals tone onset, and the third synch pulse signals delivery of the airpuff to the cornea. The output of the summing circuit can be sent directly to the tape recorder.

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NOTES

1. The KIM-1 and manuals are currently available from Falk-Baker Associates, 382 Franklin Avenue, Nutley, New Jersey 27110.

2. Synertek (Synertek Systems Corporation, P.O. Box 552, Santa Clara, California 95052) has recently announced a "SYM-2" board that is fully compatible with "SYM-1."

3. "Memory Plus" from Johnson Computer (P.O. Box 523, Medina, Ohio 44256) is a memory expansion board for the KIM, SYM, AIM family that has a built-in EPROM programmer. John Bell Engineering (P.O. Box 338, Department C881, Redwood City, California 94064) makes an EPROM programmer for the Apple computer.

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